A comprehensive approach to model abiotic resource provision capability in the context of sustainable development

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ABBREVIATIONS

AADP	Anthropogenic stock extended abiotic depletion potential
ADP	Abiotic depletion potential
AoP	Area of protection
AP	Acidification potential
BDI	Bundesverband der Deutschen Industrie e.V.
BUWAL	Bundesamt für Umwelt, Wald und Landschaft, Switzerland
CF	Characterization factors
CML	Institute of Environmental Sciences of Leiden University (Dutch: Centre for Milieuwetenschappen Leiden)
CSR	Corporate social responsibility
CO_2	Carbon dioxide
e.	equivalent
EDIP	Environmental design of industrial products
EGR	Extractable geologic resources
EMC	Environmentally weighted material consumption
EPI	Environmental performance index
EPS	Environmental priority strategies
EQD	Estimate of quantity in deposits
ESP	Economic resource scarcity potential
ETI	Enabling Trade Index
EU	European Union
GHG	Greenhouse gas(es)
GRI	Global Reporting Initiative
GDP	Gross domestic product
GTAP	Global Trade Analysis Project
GWP	Global warming potential
IA	Impact assessment
IISD	International Institute for Sustainable Development
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization

kt	kiloton
LC	Life cycle
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
MIPS	Material intensity per service unit
MJ	Mega joule
ODP	Ozone depletion potential
PGM	Platinum group metals
SETAC	Society of Environmental Toxicology and Chemistry
SLCA	Social life cycle assessment
SO_2	Sulfur dioxide
SR	Supply risk
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
USGS	United States Geological Survey

SUMMARY

Human development and technological progress depend on the availability of materials. One great challenge is to secure the accessibility and availability of resources as a basis for achieving intra- and inter-generational equity. In the context of the ever increasing amount of resources utilized, resource security is a topic of growing concern. Abiotic resources, and especially mineral resources, that are per se non-renewable are in the focus of current discussion. Abiotic resources are expected to play a crucial role for technological developments in the coming decades and are the basis for economic growth. The assessment of resource use is becoming increasingly difficult due to the high complexity and variety of materials used. For informed decision making on a product level, easy and applicable methods for the evaluation of resource availability are needed.

Even though the debate on abiotic resource availability has a long history, commonly agreed indicators for assessing resource availability are not available. For supporting decision making on a product level and in the context of achieving sustainable development, a holistic perspective needs to be applied. Life cycle based methods are considered suitable to provide support for integrating sustainable resource use into design, management and evaluation of products. However, existing approaches in life cycle assessment (LCA) only address the physical dimension of scarcity in the context of long-term concerns. These approaches neglect the immediate link of resource availability to technological progress and human wellbeing. Consideration of resource availability as an environmental problem does not live up to the whole dimension of the issue. Mineral depletion is only one of several factors that threaten availability. As resources need to be addressed in the context of their relevance for achieving human welfare the assessment of resource availability for products solely in the context of LCA is challenged in this dissertation. In the context of sustainable development goals, resource availability may be effectively constrained by economic, social or environmental factors. Resource availability assessment needs to go beyond an evaluation in LCA and shift from assessing availability as an *environmental impact* to defining resource availability as a *sustainability problem*.

The objective of this dissertation was to develop a methodological framework that allows the consideration of different aspects of scarcity in the context of retaining material security. For achieving this objective, the different dimensions of resource availability were transferred into quantifiable and robust models that can be linked to decision making procedures on a product level. Hereby, the models differentiated between an assessment of the *consequences* of resource use in products today (depletion) and the *effects* of potential constraints in the supply chain (supply risks) on current resource provision capability. The evaluation of resource depletion was revisited and, in addition, relevant economic, environmental and social constraints to resource supply were assessed.

In order to allow for a more realistic assessment of physical material availability, a new parameterization of the characterization model for the depletion of abiotic resources was introduced. Not the extraction of metallic minerals from the environment is of concern, but rather the dissipative use and loss of materials. For a holistic assessment of resource stocks, anthropogenic stocks were included into the evaluation of resource availability. By referring to the ultimate extractable amount of resources and anthropogenic stocks, the model aims at providing a comprehensive and more realistic representation of available resource stocks. Based on the new parameterization different results were obtained compared to conventional models. Materials with high anthropogenic stocks were identified as comparatively less critical than material with low anthropogenic stocks. By focusing on a sustainment of the function of abiotic resources rather than their availability in nature, the developed methodology provides incentives for sustainable resource use.

The assessment of physical resource availability was complemented by the proposal of new methodologies for the evaluation of resource provision capability under consideration of effective constraints. Goal of the developed methodologies is to quantify the effect of realities of resource production on the availability of these. The probability of economic, environmental, or social constraints within the supply chain needs to be evaluated for determining the potential scarcity of resources.

For a comprehensive assessment of resource provision capability, supply security was assessed under consideration of direct and indirect constraints. The determination of potential direct constraints encompassed the consideration of political and institutional background of resource extraction and geopolitical, political and regulatory aspects. A set of criteria that can directly constrain resource supply was identified. In the developed methodology, relevant indicators were transferred into impact factors that describe the market induced supply risk. By means of the *economic resource scarcity potential* a ranking of the overall economic supply risk of different materials is facilitated. The method provides valuable input for decision making by uncovering bottleneck along the supply chain of materials.

Indirect constraints to resource supply can occur due to poor environmental or social performance along the supply chain of certain materials and failure to comply with corporate, societal or national goals for sustainable consumption and production. Mining and processing activities are an integral part of most material cycles and the assessment of environmental impacts associated with these activities is essential for sound material choices. Non-compliance with environmental legislation or sustainable development goals can constrain the availability of resource. In the methodology developed in this work environmental impacts were transferred to environmental risk scores. The developed model enables a comparative evaluation of the environmental risk associated with different materials by means of the *environmental resource scarcity potential*. Furthermore, the social performance along the supply chain was incorporated into materials choices for promoting sustainable resource management. Due to ethical reasons and non-compliance with corporate, governmental or societal goals, and in the context of sustainable development, supply of certain materials can become constrained. By means of the methodology developed in this dissertation, the social risks associated with materials were determined. The aggregated *social resource scarcity potential* enables a comparison of the social supply risks associated with different materials.

Results differed across the different dimensions of supply risk. *Gold* for example was associated with high environmental and social supply risk but with only a low economic scarcity potential. Similarly, *silver* was associated with comparatively high economic and environmental supply risks, but only comparatively low relevance from a social perspective.

For a comprehensive evaluation of resource provision capability in the context of sustainable development, all dimensions of resource scarcity need to be considered. The comparative assessment of the different dimensions of resource scarcity revealed that resources do not have to be geologically scarce to be associated with high supply risks. For the material portfolio addressed in this work, *rare earths* and *platinum group metals (PGM)* were identified to be associated with the highest supply risk. Contrary, *rare earths* had only a comparatively low potential for depletion. The fact that materials commonly perceived as scarce, such as *rare earths*, were associated with high supply risks based on the new methods verifies the relevance and added value of the developed methods.

The significant differences of results highlight the relevance of a holistic assessment of resource provision capability. As the proposed methods are oriented towards the comprehensive evaluation of resource availability in the context of LCSA additional guidance for material choices can be provided. Based on the methodological framework developed in this dissertation, use of materials can be evaluated by taking their potential physical, economic, environmental, and social scarcity into account. This is a noteworthy improvement compared to existing methodologies. Economic, social and environmental issues related to resource provision are relevant for sustainable development complementing existing models. The developed models provide new insights and deliver a basis for the comprehensive assessment of resource availability. As the developed models can be linked to material inventories, the evaluation of resource availability associated with product systems can be significantly enhanced.

Keywords: Resource provision, scarcity, supply risk, depletion, sustainable development, LCSA

1 INTRODUCTION

Abstract

Throughout history, scarcity of abiotic resources has been an important issue, as access to resources is a prerequisite for the development of complex societies. In the context of continued high levels of resource consumption, growing world population, as well as rapid industrialization of countries like China or India, increasing concern over abiotic resource availability has been raised. Accessibility to resource to satisfy current needs of society and preserving resources for future generations and potential future uses is relevant for sustainable development. But how can global material needs be satisfied sustainably and which aspects need to be considered?

This Chapter provides an introduction to the field of abiotic resource availability and research needs are identified. The evaluation and assessment of resource availability in the context of sustainable product development is the central point of this dissertation. Whether resources will be at hand for material requirements of products depends upon physical availability in the environment and economic, environmental and social developments throughout the entire world. Scarcity of resources, whether absolute if caused by depletion of available stocks, or effective if caused by (temporary) interruptions in supply, need to be closely monitored to sustain resource availability today and in the future.

In a comprehensive literature review, existing models for the assessment of resource availability on a product-level are evaluated. So far, life cycle assessment (LCA) is the method of choice for quantifying impacts on resource availability and several approaches exist. However, a*vailable methodologies and models to address resource availability do not live up to the challenge of comprehensively addressing the problem. Availability of resources is seldom considered for product evaluations and commonly agreed indicators for identifying scarcity associated with different resources are missing.*

To understand and "uncover" constraints and risks associated with abiotic resource provision for product systems the analysis needs to go beyond the assessment of single indicators and consider the complexity of sustainable development. Instead of addressing resource availability in an environmental context, a comprehensive approach and according methodologies need to be developed towards the assessment of all dimensions of sustainability.

By including environmental, economic and social constraints into the analysis of resource availability a goal and solution oriented decision support methodology will be develop in this dissertation, facilitating material choices on a product level and complementing existing approaches.

1.1 Background and context

Natural resources are naturally occurring substances and systems that are useful to humans (Lindeijer et al. 2002; Rankin 2011). Mankind depends on natural resources, such as metals, minerals, fuels, water, land, timber, fertile soil, or clean air for survival, and these resources constitute vital inputs for a stable economy and society as well (see, e.g., European Commission 2012; Meadows et al. 2004). Natural resources are important for their structural properties (e.g., steel) and as energy carriers to humans (food) and machines (fuels). Their exploitation is strongly linked to the supply of products and services within society (UNEP 2010a, 2011a).

In recent decades, the demand for many resources has increased significantly (European Commission 2013b; Petrie 2007; UNEP 2011a; Weterings et al. 2013). However, the availability of natural resources as input for production processes is not infinite nor is the capacity of natural resources to absorb pollution (UNEP 2010a). Current patterns of resource use, the accelerating pace at which resources are exploited, and increasing pollution burdens are the basis of growing concern. In 2005, the European Commission stated the following: “If current patterns of resource use are maintained, environmental degradation and depletion of natural resources will continue”. This dissertation focuses on the analysis of the availability of abiotic resources, that is mineral resources such as fossil fuels, metallic minerals, and industrial minerals (see Moon and Evans 2006). This category of resources is of particular interest given that these resources are nonrenewable and subject to decreasing availability.

The concern that mankind will run out of mineral resources is long-standing. In 1972, the Club of Rome presented with its book, *The Limits to Growth,* a starting point to a discussion that is still ongoing (Meadows et al. 1972). Today, the topic of resource availability is more pressing than in previous times as it is a high-priority issue for economic development and implementation of technologies (Kesler 1994; Valero et al. 2013; Wäger et al. 2011). The dependency of technological developments on finite minerals has led to a steadily growing awareness of the strategic importance of sustaining resource supply (see, e.g., Abell and Oppenheimer 2008; Alonso et al. 2007; Angerer et al. 2009a; Angerer et al. 2009b; Chemetall 2009; European Commission 2010a, 2011c; Yaksic and Tilton 2009). A growing number of materials are needed to construct and maintain the complex pathways of emerging technologies and to satisfy growing demand for high-tech and clean-tech products (see, e.g., Achzet et al. 2011; Kleijn 2012) (see Figure 1). The increasing complexity of demand and supply brings with it a heightened level of risk, and the potential scarcity of abiotic resources is a matter of growing concern for many stakeholders regarding safe and continued material supply for products (see, e.g., Graedel and Erdmann 2012; Graedel et al. 2013). Furthermore, mineral resources exist at varying levels of quality and quantity, they are not equally distributed in the earth’s crust, and their extraction is determined by a number of geologic, geopolitical, environmental, and economic factors. As a result, it is impossible to correctly assess resource availability by examining past trends or focusing on single factors. Currently, the assessment of resources related to their availability for use in products is incomplete and inconsistent, and neglects relevant dimensions.

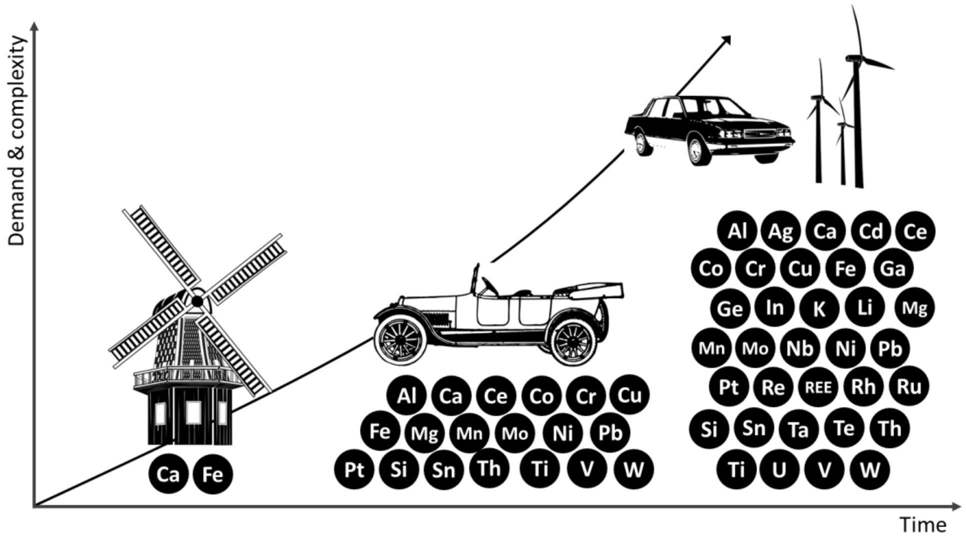

Figure 1.1: Trends in metal complexity of products (adapted from Achzet et al. 2011)

Using a comprehensive set of aspects within the framework of sustainability, this dissertation will investigate which materials are subject to potential scarcity and supply constraints and compare the availability of different materials. A comparative assessment of resource availability is important at a corporate level, to identify priorities among materials and to align strategic and economic efforts. As presented in later sections, most of the existing methods on resource availability for products examine (or at least attempt to examine) the impact of resource use *on* the environment and the availability of resources *in* the environment. The approach taken here will reassess and address the issues of resource scarcity in the context of sustainability development.

This work involves the development of a new modeling framework to examine potential material scarcity from a product perspective. The framework is built to allow the inclusion of additional aspects of resource availability into product assessments and decision making. The aim of this dissertation is to develop an applicable approach to comprehensively and comparatively evaluate potential depletion and the degree of risk associated with mineral availability, in line with current product assessment practice. In this introductory chapter, the following questions are addressed in order to define the scope and outline of this work:

- Why are we concerned about abiotic resource availability?
- What is the relevance of abiotic resources in the context of sustainable development?
- What is resource scarcity, and which aspects need to be considered?
- Which methods are available to evaluate resource availability for products and why are they not significant?
- Which gaps exist for evaluating resource availability for products, and which research needs have to be tackled to comprehensively address resource availability?

The aim of this chapter is to define resource scarcity in the context of sustainable product development, providing the frame for the forthcoming discussion and the goal and scope as a basis for the method developments in this dissertation. In the next two sections, the relevance of the availability of abiotic resources for current and future use in products is described and put in context of sustainable development. Thereafter, scarcity of abiotic resources is investigated, addressing the multiple layers of scarcity and the underlying mechanisms (Chapter 1.4). Subsequently, existing methods for assessing abiotic resource use and availability are reviewed, and their significance is outlined for addressing resource availability for products in the context of sustainable development (Chapter 1.5). Finally, existing gaps and research needs are described, and the objectives and analytical framework of this work are outlined (Chapters 1.6, 1.7, and 1.8).

1.2 Abiotic resources

This chapter defines abiotic resources as regarded in this dissertation and summarizes the importance of abiotic resources to society. Abiotic resources are chemical elements and minerals from the earth's crust. There is no other source from which they can be obtained (Kesler 2007). Abiotic resources are a real challenge to modern civilization because they form by geologic processes that are much slower than the rate at which they are exploited (Kesler 1994). Thus, abiotic resources such as metallic or energy minerals are non-renewable and cannot be regenerated within human lifetimes (UNEP 2010a).[1] Consequently, their removal and use diminishes the availability of natural stocks in the environment, that is, every consumption equates to a reduction of the natural stocks and decreasing availability for future use (Brentrup et al. 2002a; Petrie 2007).

Meeting present and future needs of mankind without abiotic resources is inconceivable. Abiotic resources are essential for the quality of life that modern society is accustomed to and play a key role in underpinning the prosperity of future civilizations (Auty 1993; Giurco and Cooper 2012; Reuter et al. 2005; Science and Technology Committee 2011; Verhoef 2004). "Easy access to [abiotic] resources is often seen as a precondition for economic development" (UNEP 2010a) as minerals and fossil fuels are crucial inputs for most production processes and are the starting material for the production of almost all manufactured products (Azapagic 2004; UNEP 2010b). Metals, for example, provide unique features and are a basic input into most products and production processes due to electrical and thermal conductivity and good processability. Without abiotic resources there would be for instance no cars, no electricity and no computers.

[1] Water and land can be included in the category of abiotic resources but are often seen as resource classes in their own rights, and impact assessment separately from other abiotic resources is common practice (see, e.g., Berger et al. 2012; Curran et al. 2011; Gontier et al. 2006; Henzen 2008; Koellner et al. 2013; Milà i Canals 2003; Milà i Canals 2007; Milà i Canals et al. 2007; Millennium Ecosystem Assessment 2005; Schenck 2001; Souza et al. 2013; Steinbach and Wellmer 2010; UNEP 2010c; Watson et al. 2005). The assessment of water, land, and the assessment of continuous resources such as sunlight and wind are excluded from this study. In some cases, natural resources are a mix of biotic and abiotic components (Lindeijer et al. 2002). In this context, it is often referred to as an abiotic factor (a nonliving component of a habitat), rather than an abiotic resource. Mineral nutrients are excluded from the focus of this dissertation, due to the different characteristics.

Demand for mineral resources has steadily increased over the past decades and continues to do so, indicating the growing importance of these resources for industrial and technological development (Behrens et al. 2007; Gordon et al. 2006; Kleijn 2012). The main drivers for rising demand include increasing standards of living, population growth, and economic growth. Furthermore, energy supply, high-tech products and emerging clean technologies are highly dependent on several metals and will thus significantly raise and change the demand for metals in the future, putting additional pressure on supply (Achzet et al. 2011; Angerer et al. 2009a; Bardi 2013; Kleijn 2012; Wäger et al. 2011). A summary of relevant drivers for increasing demand for abiotic resources is provided in Table 1.1.

Table 1.1: Trends in abiotic resource demand

Driver	Description
Population growth	Human population reached 7 billion in 2011 and is expected to further grow over the next decades. This has led to a significant increase in the use of fossil fuels and the extraction of mineral resources.[1]
Economic growth	Demand for resources will rise along with the accelerated economic growth of non-Western economies. GDP per capita and standards of living are increasing: In the past 20 years, it has grown on average by 3,8% annually. The World Bank (2014) predicts that global GDP growth will continue in the coming years. Income per capita is regarded as being one main driver for resource use.[2]
Increasing standards of living	Changing consumption patterns and higher standard of living lead to a surging demand for mineral resources. China, India, Brazil and many other developing countries will increasingly demand resource intensive products. Continued high levels of consumption in the developed world will further tighten the resource situation.[3]
Urbanization	Continuing urbanization will spur the demand of mineral resources. Urban areas have an established infrastructure and urbanization increases demand for energy, minerals and other resources. Energy and mineral resources are the key material basis for urbanization and modernization.[4]
Industrialization	Industrialization leads to increasing resource consumption as it relies on fossil fuels and minerals. Rapid industrialization of countries such as China, India and Brazil thus creates pressure on resource demand.[5]
Emerging technologies	High-tech and clean-tech products are expected to play a crucial role in the coming decades, increasing demand for resources (metals) accordingly as the metal intensity and complexity in these technologies is very high. New applications (e.g., changes in energy and transport infrastructure) can expand the market for mineral commodities considerably. The demand for metals for use in new and emerging technologies has risen in recent years.[6]

[1]Weterings et al. (2013), UNEP (2012), UNFPA (2012), United Nations (2011, 2013) [2]see Angerer et al. (2009a), Binder et al. (2006), Weterings et al. (2013) [3]Bums and van Rensburg (2012), Giljum et al.(2011), Kesler (2007) Weterings et al. (2013) [4]Binder et al. (2006), Shen et al. (2005) [5]Giljum et al.(2011), Giljum et al. (2009), UNEP (2010a), Moll et al. (2003) [6]Angerer et al. (2009b), Angerer et al. (2009c), Hagelüken and Meskers (2010), Kesler (2007), Wäger et al. (2011), and UNEP (2010a)

The rising demand for several metals increases the risk for resource scarcity. Starting decades ago, concerns over resource availability have been raised and many studies have been published in the past addressing this issue controversially (see, e.g., Angerer et al. 2009a; Angerer et al. 2009b; Bell et al. 2012; Gordon et al. 2006; Gordon et al. 1987; Kesler 1994; Kleijn 2012; Meadows et al. 2004; Meadows et al. 1972; Simon 1998; Tilton 2003; Tilton and Lagos 2007; UNEP 2010a; Wagner 2002). However, many of the concerns over potential resource shortages have not proven true so far. Mineral production could apparently be expanded in the last decades to meet increasing demand. However, declining ore grades (or quality) and increasing environmental impacts are challenges that tighten the situation of sustaining the supply for abiotic resources (see, e.g., Craig and Rimstidt 1998; Mudd 2009; Mudd 2010). Global demand of metals has increased exponentially and humankind has consumed more minerals during the past century than in all earlier centuries together (Graedel and Erdmann 2012; Krausmann et al. 2009; Tilton 2003). In Figure 2, an overview of the cumulated world production of different metals is provided. Around 80% the cumulative mine production of platinum group metals (PGM) or rare earth elements (REE) has occurred over the last 30 years (Hagelüken and Meskers 2010; USGS 2014a).

There is consensus in regarding abiotic resources as something that is subject to depletion or decreasing availability and scarcity (Steen 2006). The necessity of a sustainable use and preserving of natural resources for current and future generations is widely accepted. Resource scarcity can no longer be seen as a remote threat, as trends show that the era of cheap and plentiful resources is over (European Commission 2011c; Steinberger et al. 2010). Use and management of resources need to be laid out for securing supply and to prevent scarcity of resources for human needs. Access to abiotic resources and sufficient and secure supply of these resources well into the future are integrant in the debate on sustainable development. The relevance and value of abiotic resources in the context of sustainable development is elaborated in the next section.

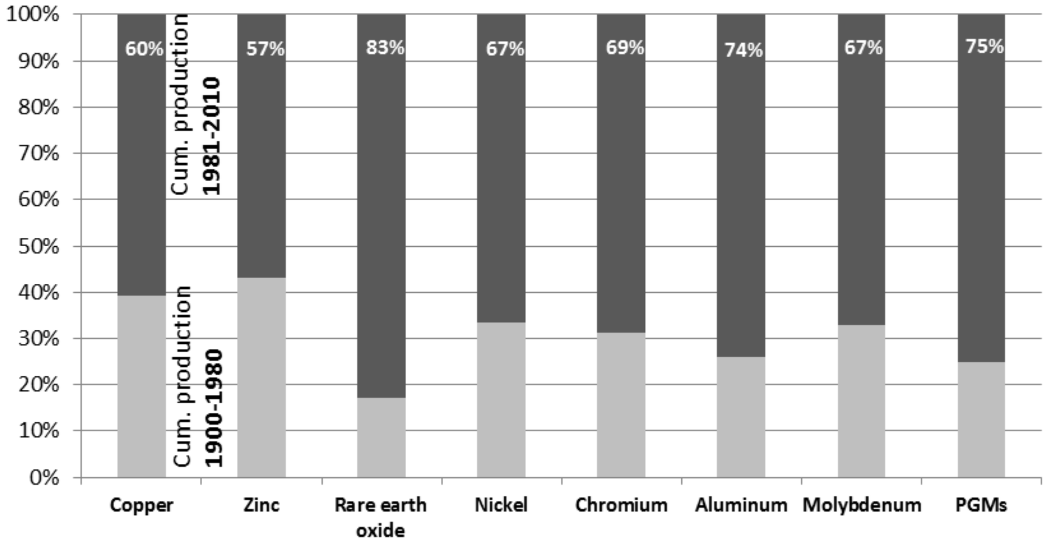

Figure 1.2: Cumulated world production of metals (based on data published by the U.S. Geological Survey, USGS 2014a)

1.3 Resource security as premise for sustainable development

What does sustainable resource use imply? It is a simple question, but regarding the use and choice of resources for the manufacturing and development of products this question becomes very complex. This section provides a short introduction to the topic of sustainability, and highlights relevant notions of resources availability in the context of sustainable development.

Sustainability is nowadays widely accepted as a guiding principle for corporate strategies and public policy makers (Finkbeiner et al. 2010). According to the Brundtland definition, the concept of sustainability aims at “development which meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987). The concept of sustainability is a wide approach and sustainable use of resources has been a topic of interest for many years.[2] A sustainable world “would have to provide material security to all its people” (Meadows et al. 2004). Access to abiotic resource is vital for modern lifestyles and quality of human life and resource shortage would have severe impacts on everyday lives and consequently on human wellbeing (European Commission 2005, 2011c; Steen 2006; Weterings et al. 2013). Yet, it can hardly be denied that a society with more abiotic reserves is more sustainable (Steen 2006). The challenge of sustainable development is to secure material supply for the welfare and wellbeing of current generations without compromising the potential of future generations for a better quality of life (IIED and WBCSD 2002; Rankin 2011).[3]

Inefficient use of resources constitutes long-term brakes on growth and negative effects on human wellbeing (European Commission 2005, 2012). Thus, sustainable use of natural resources is a key ingredient of long-term prosperity (European Commission 2005). Within the framework of environmental sustainability, sources and sinks are to be protected (Goodland 1995). Increasing use and extraction of resources as such are not sustainable in a strict sense of the word, as resources are finite and current extraction and use is depleting ore reserves (leading to an impoverishment of nature) and will diminish or limit the opportunities for future generations to use this resource (see, e.g., Hagelüken and Meskers 2010; Kleijn 2012; Lindeijer et al. 2002; Petrie 2007; van Oers et al. 2002). Thus, *sustainable resource use* is often seen an oxymoron, as use of resources in products implies exploitation of natural environment (Rankin 2011; Verhoef 2004). However, it is generally agreed that the interest of mankind is not the abiotic resource as such or its value in the natural environment (the “sake” of its existence) but predominantly the function it fulfils in the economic system (in products) and to achieve human welfare (see also Jolliet et al. 2004; Stewart and Weidema 2005; Udo de Haes and Lindeijer 2002; van Oers et al. 2002; Weidema et al. 2005; Wellmer and Becker-Platen 2002; Yellishetty et al. 2009). “If [abiotic resources] are never to be used then there is no need to maintain them for the future”(Daly 1990). Thus, the availability of mineral resources needs to be evaluated in the context of their potential to fulfill functions in products and to create value by meeting human needs (Yellishetty et al. 2011). Minerals have no intrinsic values in themselves whilst locked up in ore bodies buried in the earth and are considered to be “outside the biosphere” as a reduction of natural stocks has no direct

[2]In this dissertation, the terms ‘sustainability’ and ‘sustainable development’ are used interchangeably. The general principles of sustainability and sustainable development are taken as given in this thesis.

[3]For the assessment of resource availability, the needs of current and future generations are of relevance. The understanding of the term ‚future generations is hereby at stake. Following the definition of Jørgensen et al. (2013), the boundaries of current and future generations are vague, as generations arrive as a continuous event. Thus, no time frames are anticipated in this work.

influence on ecosystems (Petrie 2007; Udo de Haes et al. 2002). Thus, the use of resources is in line with sustainable development, for achieving *intra-generational* equity. However, next to providing resource for current generations, *inter-generational* equity needs to be considered, relating to the availability of resource for future generations. The functionality of materials can only be ensured if the material is available at a certain point in time (now or in the future). Current resource use should not deprive future generations from resources. Mineral resources that are left unexploited today can be extracted in the future. Thus, extraction and use of abiotic resources has to be evaluated in the context of limited stocks and the need to sustain use-potentials and availability over a long time period. However, considerations of sustainable use of resources do need to go beyond physical availability in the natural environment. In line with sustainability goals, the availability of resources needs to be assessed also in the context of today's use and under consideration of current constraints.

Sustainability has three aspects, or three pillars, environmental, social and economic, and it is not possible to achieve sustainability without considering all of these three aspects simultaneously (Brand 2002; Finkbeiner et al. 2010; WCED 1987). Indicators for measuring sustainable development on a product level translate sustainability issues into measures of economic, environmental and social performance with the ultimate aim of helping to address key concerns and to identify bottlenecks or hotspots in the product system (Azapagic 2004). Sustainable development is a macroeconomic problem, since it is concerned with all resources required to sustain production and the wellbeing of current and future generations (Mikesell 1994). However, sustainable development as such is mainly promoted at the micro-economic level, by pollution abatement, material efficiency, etc. The micro perspective is typically connected to decision making related to specific products or product groups (Reimann et al. 2010). Assessment of resource availability and use thus has to be implemented on a product level. The next section investigates the concept of scarcity and focuses on the different notions of scarcity.

1.4 Resource scarcity: concept and problem statement

The fundamental concern about resource scarcity is the dependency on resources that are of limited availability (UNEP 2010a). This section defines the terms "depletion" and "scarcity" for further use in this dissertation and addresses the distinction and interconnections between these two issues. This section will not be an exhaustive review of literature and concepts but will address the most basic notions of scarcity and introduces the approach to address scarcity taken up in this work. For categorization of the potential constraints, it needs to be assessed what is actually meant by "scarcity" and the different forms of scarcity need to be analyzed.

Scarcity can be defined as the lack of adequate supply to meet demand (Angerer et al. 2009a; Wäger and Classen 2006; Wagner 2002; Weterings et al. 2013). Scarcity occurs when resource provision (as a function of time) cannot keep up with demand (as a function of time), as a consequence of long-term trends or caused by temporary circumstances (see, e.g., Graedel et al. 2012b).

The assessment of resource scarcity is contested and different perceptions and perspectives exist, leading to inconsistency when discussing and evaluating the problem of resource scarcity. In general two questions are relevant: *How much is left? And how much is accessible?* For investigating the potential scarcity associated with materials, and to determine the risk associated with sustained production these questions establish a framework for further analysis. Scarcity can be understood as a *consequence of extraction, use and ultimately depletion* of natural resources. The underlying concern here is the exhaustion of a material or resources, leaving future generations with fewer opportunities to satisfy their needs. However, resource availability for products has a second dimension: Scarcity can also result as a consequence of temporary *disruptions in the supply chain*. Supply risks that originate from constraints within the supply chain need to be evaluated. In the following these two notions of scarcity will be explained in more detail.

"Mineral supply starts with the physical existence of materials, and can be no greater than its occurrence in the Earth's crust" (Brown 2002). The direct impact related to the use of abiotic resources are denoted as the *depletion* of resources (UNEP 2010a). *Depletion* can be defined as the process of exhausting the abundance or availability of resources and occurs due to diminishing volumes or a deteriorating quality of the available stocks (Guinée and Heijungs 1995; Guinée et al. 2002; Lindeijer et al. 2002; Radetzki 2002). Hence, *depletion* refers to the decrease of the physical amount of a resource that is available for (future) human use and can thus be described as *absolute* or *physical scarcity*. In current literature, depletion is assessed by means of

- purely physical aspects, referring to the decreasing stocks of materials,[4] or
- increasing expenses of resource extraction associated with decreasing resource stocks, assuming that costs of producing minerals will rise to a point where they are no longer affordable (see, e.g., Tilton 2003).[5]

The first notion is based on the growing consumption in the context of finite resources, implying approaching of a physical limit and exhausting the resource in an absolute sense. This could have negative impacts on a global scale and is certainly opposing the principles of sustainable development. However, the definition of available physical stocks leaves large room for interpretation and is often related to economic considerations and assumptions. This leads to the second notion, which is based on the increasing expenses of resource extraction. Increasing costs associated with the extraction of resources can be related to decreasing ore-grades and deposit size (Skinner 1976; Vieira et al. 2012).[6] High demand of energy and increasing costs can lead to constrained availability of mineral resources, even before the

[4] This perspective is also known as the Malthusian perspective, referring to the limited size of resources (Malthus 1798).

[5] This perspective can be described by means of the opportunity cost paradigm or the Ricardian perspective. The opportunity cost paradigm „assesses long-run trends in availability by real prices or other measures of what society has to give up or sacrifice to obtain another ton material" (Tilton 2003). Similarly, the Ricardian perspective takes the notion that high extraction costs could limit mineral resource availability before exhaustion is reached (Barnett and Morse 1963; Ricardo 1821).

[6] Low grade deposits are likely to be more difficult to mine than high-grade deposits. As a results, energy required could be one or two orders of magnitude greater when metals would need to be extracted from low grade deposits, causing a significant increase in costs (Skinner 1976).

maximum extractable amount of the resource has been exploited. Such parameters are often assumed to determine the limits to growth and constrain supply in the end (see, e.g., Bardi 2011; Meadows et al. 1972; Turner 2008).

Fierce debates have been going on around the questions whether increasing costs and prices, new discoveries and exploitation, technological progress, substitution or recycling and reuse can in the long run compensate for decreasing ore grades, diminishing resource stocks and lower quality (Bentley 2002; Kesler 2007; Kleijn 2012; Prior et al. 2012; Radetzki 2002; Simon 1998; Simon 1980; Tilton 1996; Tilton 2003; Tilton and Lagos 2007).[7] However, it is very likely that those measures can only prolong resource accessibility within certain environmental and social limits and under economic and geopolitical constraints (see, i.a., Brown 2002; Giurco et al. 2010; Kleijn 2012; Mudd 2010). The fast changes in products lead to changes in metal demand but production and recycling routes develop only gradually over time and in the context of ever increasing demand for resource recycling can only cover part of demand (Reuter et al. 2005; Steinbach and Wellmer 2010). Beyond that, future mining will likely be associated with more intense environmental repercussions due to higher requirements on drilling, mining, and refining (European Commission 2010c; Humphreys 2010; Mudd 2010; Norgate and Haque 2010; Norgate et al. 2007; Skinner 1976; Yellishetty et al. 2011). The exhaustion of individual materials would deprive future generations from using this material, rendering potential substitution of materials as such unsustainable. Additional discussion on costs and prices in the context of scarcity is provided in Box 1.1. Considering the described shortcomings, the most appropriate way to determine potential physical scarcity of a resource is seen in the assessment of existing stocks.

While depletion, resulting in *absolute or physical scarcity*, refers to a long-term process (van Oers et al. 2002), scarcity can also occur in the short-term and refers to the decreased availability of abiotic resources in the context of (temporary) constraints in the supply chain (see also Finnveden 1996; Heijungs et al. 1997; Lindeijer et al. 2002). Even if materials are "physically" abundant, efforts of recovery, social and environmental issues associated with mining and processing or political factors might restrain availability and lead to *effective scarcity* of a resource (see also Brown 2002; Hewett 1929; Meadows et al. 2004; Rosenau-Tornow et al. 2009). Low transparency, political efforts to support domestic industries, complex and intertwined supply structures, as well as legal, tax, and environmental regulations can impair the functioning of markets and can result in interruptions in the supply chain of a resource (Bardt et al. 2013; Kesler 1994).

[7] While resource optimists have posited that technological developments, new discoveries and exploitation or material substitution will alleviate the seriousness of resource scarcity, resource pessimists exhort that natural resource exhaustion, growing energy demands and environmental damages associated with mining and mineral production will significantly constrain resource supply. Arguments on both sides are clearly valid and highlight the complexity and uncertainty associated with the analysis of resource availability.

Box 1.1: Mineral economy – Prices and costs as a signal of scarcity?

Economists argue that resource scarcity will automatically be reflected in prices which in turn would decrease demand (and extraction) of minerals. In the past, natural resources prices and costs of extraction have declined simultaneously with increasing production which is often interpreted as a sign for decreasing scarcity (Reynolds 1999). Thus, long-run mineral price trends offer little support for arguments for depletion (Krautkraemer 2005; Petersen and Maxwell 1979; Tilton and Lagos 2007; UNEP 2011a). However, there has been a general critique of costs and prices being used to indicate or even predict resource scarcity. In the following bullet points some of these shortcomings are addressed.

1. As of the time being, the costs of extraction do not reflect the full social and environmental price of extracting resources. For the resource market to correctly display resource availability, social and environmental consequences of mining would have to be internalized. So far, such consequences have largely been externalized from the cost of production (see, e.g., Prior et al. 2012). Thus, this approach is associated with many uncertainties and does not properly display the expenses of resource extraction and consequently the (sustainable) limits to availability.

2. Current exploration activities give hints on future resource discoveries, due to increasing knowledge about, for example, characteristics of resources and likely mineralogical formations and distribution. The more information about deposits is available, the cheaper it is to find new deposits as the learning process can lead to decreasing costs (Steen 2006). With higher information, the probability of finding new resource increases. However, eventually less resources will be found at a given level of effort as the learning process levels out and less remains to be found (Reynolds 1999; Steen 2006).The true size of the ultimately extractable amount of resources is never known. Society does not know if technology is actually overcoming scarcity or not until demand for a resource outstrip supply. Thus, true scarcity is only revealed towards the end of exhaustion (Reynolds 1999).

3. Prices are only affected by current resource demand. Future generations are excluded from price formation. In this sense, the inter-temporal equitable distribution of mineral and metal resources is not achieved by means of assessing prices (Frischknecht and Büsser-Knöpfel 2013).

4. Cost-reducing effects of new technologies can offset cost increasing effects of depletion which is not in line with sustainable thinking.

5. Actors may sell well below costs, build stocks or withhold resources form the market, falsifying and manipulating prices and conclusions regarding the actual scarcity of a resource.

As market prices rather reflect the cost of extraction and processing and depend on energy prices, do not include external costs of production, underlie increasing participation of speculative investors and are affected by international trade and cartels, prices cannot serve as a good proof or disproof of scarcity (see, e.g., Chapman and Roberts 1983; DeYoung Jr. et al. 1987; Kaminska 2009; Norgaard and Leu 1986; UNEP 2010a).

Non-economic (or non-market conform) behavior of actors in the markets can distort actual scarcity of resources and lead to wrong conclusions. Resource deposits and production activities are locally limited and high investment and long lead times hinder the rapid expansion of exploitation activities. Trends in the mining sector do not seem favorable for rapid expansion of mining and for several materials there is no known substitute for certain applications (e.g., *chromium* in jet engines) (Hill 2011; Kleijn 2012). The true size of the ultimately extractable amount of resources is never known and appropriate mechanisms to include external costs of mineral extraction and processing into the practice are still missing. Thus, many authors suggest that market forces are inadequate to successfully manage the problems of resources availability and use, and to offset resource shortages even in the short term (Alonso et al. 2007; Kleijn 2012).

In Figure 1.3 an overview of the two types of scarcity described previously is provided, reflecting the differentiation employed in this dissertation. Any kind of scarcity is relevant and can have consequences on manufacturing industries and product implementations. Especially in the short run, demand for metals tends to be very inelastic, as manufacturers have limited ability to adjust production levels, product features, or production equipment quickly (Bardt et al. 2013; Rosenau-Tornow et al. 2009). Shortages in resource supply pose a threat to the viability of products and can negatively affect the ability to maintain and expand the man-made environment and impede sustainable development (Goedkoop et al. 2008).

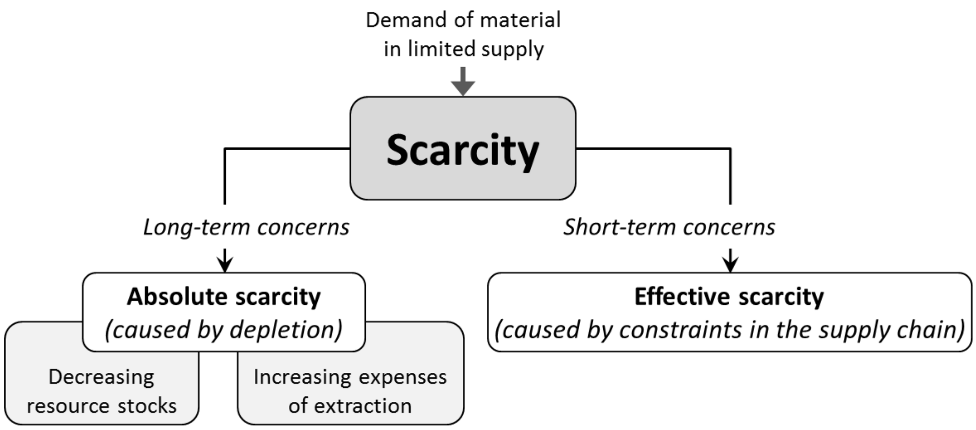

Figure 1.3: Physical and effective scarcity

In the following, the two notions of scarcity are elaborated and the means by which scarcity can be evaluated are described. For the evaluation of physical scarcity the classification of resource stocks is described in the context of long term evaluation of resource availability. Effective scarcity is addressed by providing a description of possible constraints in the supply chain that can lead to disruptions of supply.

1.4.1 Physical scarcity: determination of physical limits

If we use resources now, fewer resources will be available for future generations. Depletion is caused by the use of resources in today's products and will affect future availability of resources. To determine the potential physical scarcity of resources, appropriate measures need to be identified, referring to the stock of resources and their rate of depletion.

The earth's crust is the ultimate source of minerals used by humans and the supply of minerals is geologically fixed (Rankin 2011). The availability of mineral resources can be expressed in terms of their concentration in the earth's crust. A mineral *deposit* is an unusually high natural concentration of mineral matter in the earth's crust (Govett and Govett 1976).[8] Deposits are fixed in quantity and are not regenerated within human lifetimes (van Oers et al. 2002). When elements within the minerals can be recovered at a profit the deposits become *ores* (Aspermont Media 2013; Hustrulid and Kuchta 2006; Kesler 1994; Misra 2000; van Oers et al. 2002). The abundance of individual minerals in the earth's crust varies greatly. There is only a certain amount of each element available that can ultimately be extracted due to favorable geologic and physical conditions (see Box 1.2 for further elaboration). Mining is only possible where resources are geologically present or abundant (Gerber and Warden-Fernandez 2012). However, the size of the "entire" resource deposit is unknown.

Box 1.2: The physical limits of extraction

According to Skinner (1976, 2001) the distribution of grade and amount of metallic minerals is normally bell shaped, differentiating between *major* and *minor* elements (see Figure 1.4). This thinking about the distribution of elements in the earth's crust is followed by many geologists (e.g., Gordon et al. 2007; Tilton 2003). The largest part of an element is not and will never be economically extractable, because the grades are too low (e.g., presence of minerals in normal rocks).

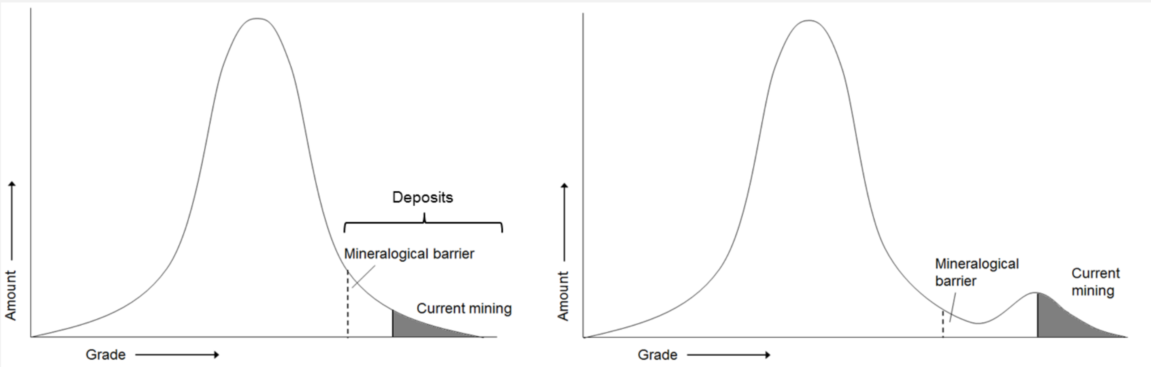

Figure 1.4: Distribution of major (left) and minor (right) elements in the earth's crust (after Skinner 1976; Skinner 1979, 2001)

[8] Nonconventional mineral deposits, such as ocean resources (e.g., polymetallic massive sulphide deposits or manganese nodules and cobalt-rich crusts) are not considered in this work as these resources are as of today not ready to be exploited with given technology and are associated with high uncertainties (DeYoung Jr. et al. 1987). As grade in the ore body decline, developing ocean resources will likely gain relevance for some elements, e.g., *calcium* or *magnesium* (Giurco and Cooper 2012; Rankin 2011). However, costs of producing those metals would be prohibitive in many cases (Rankin 2011).

When addressing resources stocks, the so-called *mineralogical barrier* separates the smaller amount of minerals at higher concentrations and in easily accessible form (*deposits*) from the larger amount of a metal at lower concentrations in more tightly bound form (Skinner 1979). To produce metals from ordinary rocks would imply a “jumping” over the mineralogical barrier and would be associated with significantly higher energy requirements, water use and pollution and is subject to thermodynamic limits (Gordon et al. 2007; Skinner 1979). The costs of producing metal concentrates form crustal (common) rock, beyond the mineralogical barrier, is one to two orders of magnitude higher than the cost of today’s processes (Rankin 2011; Steen and Borg 2002).

The *ultimate reserves* are defined as the amount of resources that is ultimately available in the earth’s crust (natural concentration of the resource multiplied by the mass of the crust) (Guinée 1995; van Oers et al. 2002). The amount of any particular element in the Earth’s crust is fixed.[9] Different approaches exist for quantifying the availability of mineral resources. These approaches are closely linked to economic considerations and result in different stock figures. Following a classical understanding, stock classification is based on geologic or physical characteristics (e.g., grade[10] or tonnage) and on the analysis of economic profitability.

A widely accepted classification of earth’s resources has been published by the U.S. Geological Survey (USGS 2014b). *Resources, reserve base* and *reserves* describe amounts of minerals in deposits (tonnage of material) with different anticipated time horizons concerning availability (Misra 2000; USGS 2014b). A *mineral resource* is a concentration or occurrence of mineral of economic interest in or on the earth's crust in such form, quality and quantity that economic extraction is currently or potentially feasible (Gordon et al. 2006; Kapur and Graedel 2006; USGS 2014b). A distinction is made between identified and undiscovered resources. Estimates of global resources can change over time and are based on known locations or estimates from specific geological knowledge, but with varying degrees of geological certainty (USGS 2014b). That a resource is known to exist does not automatically mean that it will ever be exploited (Crowson 2011). *Resources* include undiscovered deposits, regardless of economic or technological factors (Kesler 1994). *Reserve base* refers to that part of a *resource* that meets specific physical and chemical criteria, related to current mining and production practices[11]. However, only those deposits can be exploited as of today that are accessible using existing technologies and that are rich enough to be mined economically. These deposits are termed (economic) *reserve* and refer only to those resources that can be extracted at a profit now or in the near future (Kesler 1994; Kleijn 2012; Misra 2000). *Reserves* include only recoverable materials, but the term *reserves* need not signify that extraction facilities are in place and operative (Sievers 2012; USGS 2014b). In Figure 1.5 an

[9]Other authors refer to those *ultimate reserves* as *resource base*, which refers to „all the copper in the earth’s crust“ (Tilton and Lagos 2007) and is thus equivalent to the definition of *ultimate reserves*.

[10]Grade is the average concentration of a valuable substance in a mineral deposit (Misra 2000).

[11]The reserves base was used as an estimate of the size of those parts of resources that had reasonable potential for becoming economic within planning horizons. However, these estimates were based on expert opinion rather than on actual data. The USGS discontinued reporting of estimates of the reserve base in 2010.

overview of this classification of earth’s resources is provided and the relation between *reserves*, *reserve base*, *resources* and *ultimate reserves* is illustrated considering their stage of development.

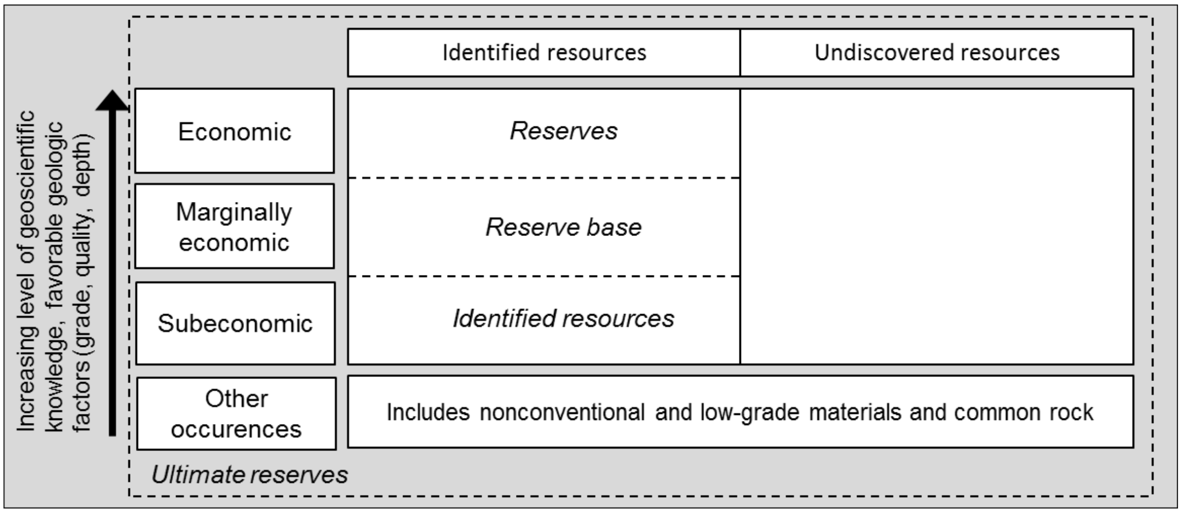

Figure 1.5: Mineral resource classification (not drawn to scale) (adapted from Gordon et al. 2006; Kesler 1994; Kleijn 2012; SAMREC 2000; Tilton and Lagos 2007; USGS 2014b)

The question of how much mineral resources are actually there is very challenging and high degrees of uncertainty exist with regard to quantifying resource deposits (Graedel et al. 2011b). The geologic concept of mineral deposits is complicated by price, grade, and technology. Increasing levels of geoscientific knowledge, technological developments and increasing resource prices promote a shift towards *reserves*. Parameters like *reserves* or *reserve base* are not static and change over time, in line with exploration activities, material prices, new technologies and other factors (Barton 1983; Crowson 2011; Graedel et al. 2011b; Steen 2006). Consequently, *reserves* or *reserve base* do actually not account for the amount of metal that can be found in the earth’s crust and are no indicator for potential physical exhaustion. In Figure 1.6 an overview of the development of *reserves* of *copper* and *zinc* is displayed to highlight their changing nature.

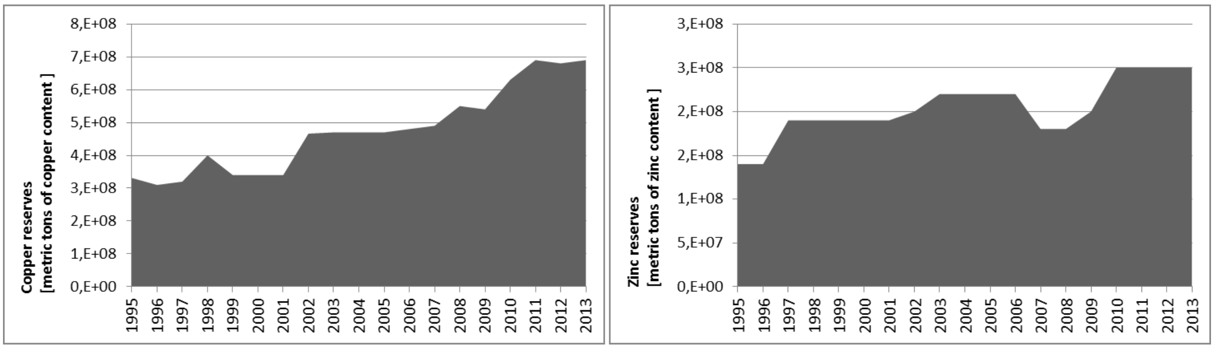

Figure 1.6: Economic reserves 1995 - 2013 – *Copper* (left) **and *zinc*** (right) (based on data from the U.S. Geological Survey, USGS 2013a)

Guinée (1995) highlighted that the consideration of the *ultimately extractable reserve* would be the relevant parameter with regard to assessing the geologic availability of mineral resources for human needs, following the classification according to Skinner (2001) (see also Graedel et al. 2011b; Rankin 2011). However, as Guinée (1995) pointed out, data on this type of reserve are hard to find and will never be exactly known because of their dependence on many parameters like future technological developments. Several studies have tried to estimate the total quantity of an element that is above of the mineralogical barrier (see, e.g., Graedel et al. 2011b).[12] According to Rankin (2011) availability in the crust is proportional to the combined size of deposits of a particular element.[13] This opinion is also supported by the *Working Group on Geological Stocks of Metals* of the UNEP International Panel on sustainable Resource Management (Graedel et al. 2011b). Consequently, to compare the physical scarcity of resources, the evaluation of the crustal abundance (ultimate reserves) or the extractable global resource would lead to the same result. Thus, for a comparative assessment of physical scarcity in the context of models like the ADP, both measures are appropriate.

When trying to determine the availability of resources for future generations, the fact that resources are not depleted by use but rather transferred from the earth's crust into the anthroposphere needs to be taken into account. From a functional point of view, it is irrelevant whether the resource is available in the environment or economy if the function at present attached in economic goods is still available for future applications (van Oers et al. 2002). Materials like *copper* or *aluminum* can be recycled and thus still fulfil a function within the economy. However, if the material is dissipated[14] and is not present in sufficient quality anymore, its potential functions will be lost for mankind (van Oers et al. 2002). Thus, for an evaluation of physical availability of materials, the extent to which metallic minerals can be recycled and reused needs to be acknowledged and stocks in the anthroposphere need to be considered as well. Urban mining (recycling) can be seen as an important measure for (future) resource supply (Klinglmair et al. 2013; Müller-Wenk 1999). A differentiation between dissipative and non-dissipative use is needed for assessing potential resource depletion (see, i.a., Goedkoop and Spriensma 2000).

The physical abundance as discussed in this chapter plays a role for the availability of resources, but so do other factors such as environmental impacts, social disruptions, political barriers, etc. An overview of aspects potentially leading to effective scarcity of resources is given in the next section.

1.4.2 Effective scarcity: constraints in the supply chain

Much of the recent debate has focused on the availability on mineral deposits, rather than considering other potential constraints. Availability and security of resource supply for

[12] Using ore below the mineralogical barrier would hardly be acceptable. Due to increasing costs of extraction and technological limits a material would no longer be available (see Box 1.2).

[13] This assumption is based on a case study by Skinner (1976), identifying the amount of copper above the mineralogical barrier.

[14] Dissipation refers to the state where elements become so dilute or change their chemical form so they can no longer fulfil a required function (UNEP 2010a).

current production depends on the timely access to resources (Rankin 2011). This section provides an overview of potential constraints to abiotic resource supply that could lead to *effective scarcity* of a material. Effective constraints have their origin often in the increasing competition over resources and political and regulatory rules or in societal goals and potential negative societal impacts.

Supply chains for materials are very complex and globalized (Buijs and Sievers 2012; Rungi 2010). In this context, traditional geologic constraints are joined by additional limitations imposed by market control and trade networks. Trade and dependency on trade can exert pressure on the accessibility of mineral resources and can affect availability of resources for products, at specific production sites or in certain countries. Increased government interference may have a significant effect on free markets and constrain resource supply. Some resources are short in supply not because of geologic depletion but because they are located in only few areas in the world. The differences in global capital among nations and geopolitical and regulatory causes may effectively provoke scarcity due to disruptions of supply (Wolfensberger et al. 2007).

The supply chain of a material is a relevant part of the life cycle of a product. Constraints affecting the continued supply of certain resources can occur at any stage of the supply chain. Limitations in resource supply may be imposed by the state of technology, social or economic developments, or the environmental impacts of extraction (following the definition of United Nations (1987) and USGS (2014a)). To identify potential scarcity of resources several factors need to be considered and evaluated with regard to the risk of their occurrence. Environmental (can we extract and process it with a level of environmental damage that society considers acceptable?), economic (how do policies, economic systems, supply chains affect availability?) and social (can we extract and process material with effects on communities and humans that society considers appropriate?) aspects need to be considered (see Graedel et al. 2012b).These factors can refer to policy and regulatory risks, market risks, geopolitical risks and so on. Not all abiotic resources are similarly affected by the described constraints and not all constraints pose an immediate threat to supply.

The evaluation of effective as well as physical scarcity within this dissertation and the design of the model developed in this dissertation will be described in Chapter 2. In the next section an overview of available methodologies and models for assessing resource use and availability on a product-level is provided, focusing on the suitability of these models to address resource scarcity.

1.5 State of the debate: review of methods and discussion

This chapter captures the state of the art resource availability assessment and current approaches for evaluating the use of natural resources in products are reviewed. First, an overview of existing methods is provided. Hereby the focus is on methods for addressing resources use and availability on the product-level, in line with the scope of this work.

Thereafter, shortcomings of the different methods are discussed in the context of their applicability and reliability for addressing resource availability or scarcity.

Today, many studies focus on increased resource productivity, increased eco-efficiency or energy reduction and the assessment of environmental problems of resource extraction and processing is widespread (Ditsele and Awuah-Offei 2012; Durucan et al. 2006; Klinglmair et al. 2013; Swart and Dewulf 2013). The importance of improved resource management for sustainable development is widely accepted and literature addressing sustainability topics related to extraction and use of minerals is broad (see also Giurco and Cooper 2012). There are various initiatives and activities on a national and regional level, as well as in the minerals and mining sector itself that aim for a more sustainable future with sustained supply of mineral resources and a range of indicators and methods have been proposed to assess abiotic resource utilization in the context of constrained availability (i.e. Azapagic 2004; European Commission 2005, 2010a; European Commission 2011b, c; IIED and WBCSD 2002). However, the methods and indicators have been developed and applied independently from evaluations on a product level and mostly address aggregated material flows of a certain material without a direct link to resource scarcity. Economy-wide indicators cannot easily be transferred to a product-level and can thus not deliver decision support regarding the choice or comparison of materials for products. In the following an overview of existing approaches for addressing abiotic resource utilization on a product level is provided.

1.5.1 Methods and indicators on a product level

The availability of resources is a relevant variable in decision making on the product level. Product designers need to employ materials that are not scarce or subject to supply restrictions or disruptions to sustain industrial production. Currently, many concepts for assessing resource use are based on an evaluation of the mass of resources used in relation to the value added and aim at a shift away from resource-intensive production processes and consumption patterns. Resource utilization on a product level is often assessed by means of mass- or energy-based indicators. For example, the Wuppertal Institute developed an indicator to measure the quantity of resources used for a specific product of service (Material Input Per Service unit, MIPS) (Ritthoff et al. 2002). The MIPS-indicator hereby takes into account all material inputs required to produce a product or service. A similar approaches is adopted with an indicator displaying the cumulated energy demand, indicating the primary energy demand along the entire lifecycle of a product (Fritsche et al. 1999; Institut für Ökologie e.V. 2008). However, similar to mass-based indicators on a national level, these indicators are simply referring to the material inventory and a scientific link to scarcity is missing. Furthermore, based on these indicators no statement can be made with regard to the effects of resource use on the environment, human health or availability of these resources in nature.

Next to these stand-alone methods, comprehensive approaches are available for addressing and evaluating resource use in products focusing on the entire life cycle. “Any resources measurement system that is intended to support decisions at a national, sectorial or product level should apply a life-cycle perspective" (Giljum et al. 2011). Life cycle thinking represents the basic concept of considering the whole product system life cycle from the "cradle to the grave". This is an important basis for the assessment of resource use, at it prevents shifting of environmental burdens or neglecting of problems and furthermore aims at uncovering potential "problems" within the life cycle. Life cycle based methods are considered suitable to provide support in integrating sustainable resource use into design, innovation and evaluation of products (Klinglmair et al. 2013; Sala et al. 2013). For evaluation of products in a life cycle context several methods are available (see Box 1.3).

Box 1.3: Methodological toolbox

Life cycle assessment (LCA)

LCA is one of the most widely accepted and developed tools for evaluation potential environmental impacts throughout the lifecycle of a product. LCA aims at quantifying "all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services (products)" (European Commission 2010b). Evaluation of resource use and availability is common practice within LCA. The assessment of the use of abiotic resources is usually part of the life cycle impact assessment. (European Commission 2010c; Finkbeiner et al. 2010; ISO 14040 2006; ISO 14044 2006; van Oers et al. 2002).

Social life cycle assessment (SLCA)

Social LCA (SLCA) is an "*emerging tool to measure the social-related impacts in the supply chain*" (Benoît-Norris et al. 2012). Social LCA aims to assess the social impacts along the life cycle of a product. Social impacts are consequences of social interactions weaved in the context of a production process. SLCA provides information for decision makers and aims at promoting the improvement of social conditions in product life cycles (Benoît et al. 2010). SLCA in general aims at capturing societal impacts on different stakeholder categories. The S-LCA framework recommends the consideration of five different stakeholder categories[15] and a total of 31 subcategories. The subcategories address socially significant themes or attributes. The social impacts depend highly on the geographic location (Benoît-Norris et al. 2012; Norris et al. 2014; UNEP/ SETAC 2009). So far, SLCA has not been linked to evaluate availability of abiotic resources. However, identified indicators and impact categories are equally meaningful for abiotic resource assessment.

[15] A stakeholder category is a cluster of stakeholders that are deemed to be potentially impacted by the life cycle of a product. Five main stakeholder categories are differentiated: workers, local community, society, consumers and value chain actors (UNEP/ SETAC 2009).

LCA-type life cycle costing (LCC)
The life cycle costs are the total costs of a system or product (Finkbeiner et al. 2010; Kaufman 1970). LCA-type life cycle costing (LCC) is excluded in this work as it does not "live up to the global scope of sustainable development" but rather describes economic performance of companies (Jørgensen et al. 2010a). Even though LCC might be applicable in some situations (Klöpffer and Ciroth 2011), it has no direct relation to maintaining resource supply. Furthermore, prices of materials have, as elaborated earlier, no direct relation to potential scarcity of certain materials. For the identification of economic or market risks along the supply chain of materials, monetary flows can deliver no insight into the potential scarcity of resources and other indicators are needed.

Life cycle sustainability assessment (LCSA)
According to the United Nations Environment Programme (UNEP 2011c) LCSA is "the evaluation of all environmental, social, and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life-cycle". Within LCSA environmental, economic and social impacts of products are assessed (European Commission 2010b; Finkbeiner et al. 2010; Klöpffer 2008). The methodology of LCSA provides a framework for the comprehensive evaluation of economic and social impacts of products, in addition to environmental ones (Finkbeiner et al. 2010; Klöpffer 2008; UNEP 2011d). The role of LCSA is to assess the extent to which a product life cycle affects the meeting of needs of present generation or the ability of future generations to meet their needs. The LCSA framework has been put into a conceptual formula (Finkbeiner et al. 2010; Klöpffer 2008): LCSA = LCA + LCC + SLCA

Life cycle assessment (LCA) has proven to be a valuable tool for evaluating the potential environmental impacts of products and materials and can be considered to be common best practice for the evaluation of resource use. Many companies are applying LCA as one of the important tools in evaluating their environmental performance (Yellishetty et al. 2009). Within LCA, the assessment of resource is based on the need to protect the natural environment and to preserve resource availability in nature. Evaluation of resource use and availability is common practice within LCA (European Commission 2010c; ISO 14040 2006; ISO 14044 2006). Currently, most life cycle impact assessment (LCIA) methods are concerned with the assessment of the environmental dimension of resource extraction, modeling the effects on the *natural environment* (e.g. global warming potential, acidifying potential, ozone depletion potential). Furthermore, 'natural resources' are defined as an area of protection (AoP)[16] referring to the need to preserve resource availability. Several authors address the effects of natural resource use and proposed ways to integrate resource depletion into the LCA framework. As of today, a wide variety of LCIA-methods has been developed that address the physical dimension of resource scarcity. All available methods focus on the decreasing geologic availability of abiotic resources but address different levels. Midpoint

[16]The societal values can be grouped into different areas of protection (AoP). Within LCA, mainly three AoPs are differentiated: 'human health', 'natural environment', and 'natural resources'.

approaches start at the environmental intervention and describe the mechanism of depletion. Endpoint approaches addresses the damage level and attempt to capture the consequences of resource extraction (see, i.a., Klinglmair et al. 2013; Udo de Haes and Lindeijer 2002). The distinction between mid- and endpoint categories is not very clear for resource depletion, as the impact category (resource depletion) and area of protection (natural resources) are congruent.

Existing models for the assessment of resource availability in LCA relate to energy and mass of a resource used, exergy or entropy impacts, future consequences of resource extraction (e.g. surplus energy, surplus cost) or diminishing geologic deposits (see, i.a., Bösch et al. 2007; BUWAL 1998; Dewulf et al. 2007; European Commission 2010c; Finnveden et al. 2009; Finnveden and Östlund 1997; Goedkoop and Spriensma 2000; Guinée et al. 2002; Hauschild and Wenzel 1998; Klinglmair et al. 2013; Lindeijer et al. 2002; PE International 2013; Steen 2006; Stewart and Weidema 2005; van Oers et al. 2002). In Table 1.2 an overview of the different LCIA-methods is provided with regard to available mid- and endpoint metrics and the underlying concepts (based on European Commission 2011a; Klinglmair et al. 2013; Pennington et al. 2004). All indicators have in common that they aim at expressing decreasing availability of resources either based on the physical finiteness of resources or with regard to future consequences of the extraction (depletion) of a resource (Klinglmair et al. 2013) assuming that extraction today will lead to lower availability or higher costs of resource extraction for future generations. The shortcomings of the individual methods are discussed in more detail in Chapter 1.5.2.

Table 1.2: LCIA methods for resource depletion

Method	**Characterization factors**				**Reference**
	Midpoint		**Endpoint**		
	Unit	Concept	Unit	Concept	
CML 2002 (ADP-method)	kg Sb-e.; MJ	Reserves and annual extraction rates	-	-	Guinée et al. (2002), van Oers et al. (2002)
Eco-indicator 99	-	-	$MJ_{surplus\ energy}$	Surplus energy	Goedkoop and Spriensma (2001)
Ecoscarcity 2013[1]	UBP/g kg Sb-e.; UBP/MJ oil-e.	Distance-to-target (weighting method)	-	-	Frischknecht et al. (2009)
EDIP 1997[2]	Person-reserve	Reserves and extraction rates	-	-	Hauschild and Wenzel (1998)
EPS 2000[3]	-	-	$\$_{WTP}$	Willingness-to-pay	Steen (1999)
Exergy	MJ_{exergy}	Loss of exergy	-	-	Finnveden and Östlund (1997); Dewulf et al. (2007)
IMPACT 2002+[4]	kg Fe-e.; MJ	Mineral extraction	$MJ_{surplus\ energy}$	Surplus energy	Jolliet (2008), Humbert et al. (2012)

Method	Characterization factors				Reference
	Midpoint		Endpoint		
	Unit	Concept	Unit	Concept	
LC-IMPACT[5]	%/kg	Decrease in ore grade due to increasing extraction	$/kg	Surplus cost increase as response to lower ore grade	Vieira et al. (2011)
LIME	Sb-e. kg; MJ	Consumption energy, reciprocal of recoverable reserves	¥	User costs (displaying costs of overuse)	JLCA (2012)
ReCiPe[6]	kg Fe-e.; MJ	Decreased concentration	$\$_{\text{surplus cost}}$ ($/kg)	Surplus cost/damage to resource cost	Goedkoop et al. (2008)

[1]Distance-to-target approaches set environmental interventions against predefined targets. The characterization factors in this method are based on Guinée (2002) but are transferred to EcoPoints (EP) via weighting of the characterization factors. [2]Method involves normalization and weighting. Amount of the resource extracted is normalized to the average annual consumption of one world citizen and weighted according to the static lifetime of available economic reserves (European Commission 2011a; Hauschild and Wenzel 1998). [3]The method of Environmental priority strategies (EPS) accounts for the monetary cost of avoiding damages to natural resources. [4]Damage CFs are taken directly from Eco-indicator 99. The midpoint CFs are obtained by dividing the damage CF of the considered substances by the CF of the reference substance (iron). However, midpoint indicator are not recommended for use (Humbert et al. 2012). [5]The midpoint method is not applied, as no linear relation to the endpoint exists. The endpoint is calculated as the ratio of predefined critical flow to the actual flow of a resource. [6]The method uses increased costs as endpoint indicator and 'the slope (relation grade-yield) divided by availability' as midpoint indicator (Goedkoop et al. 2008).

As highlighted in earlier chapters, the geologic availability of resources is only one of several factors affecting resource availability. The consideration of additional dimensions of resource availability, considering stocks in the anthroposphere or addressing the effective scarcity of resources, in the context of product assessments is currently neglected.

The assessment of economic aspects related to resource availability, addressing the *effective scarcity* of resources along the supply chain, has gained some attention over the past years. Various papers and working groups are dealing with the determination of risks associated with resource supply (Angerer et al. 2009a; Angerer et al. 2009b; Defra 2012; Erdmann and Behrendt 2010; European Commission 2010a; Graedel et al. 2012a; Nassar et al. 2012; National Research Council 2008; Nuss et al. 2014; Rosenau-Tornow et al. 2009; VDI 2013). The focus of these papers is on the identification of potentially critical materials for companies or countries. Several indicators were introduced assessing the supply risk considering economic indicators and vulnerability of countries or companies to supply disruptions. Supply risks addressed refer to interruptions in the supply chain due to market imbalances, political risks, etc. The proposed indicators are effective and applicable for assessing scarcity. However, the definition and determination of supply risk is complex and existing methodologies are often immature and lack transparency. Thus, the results are not necessarily helpful (see also Buijs et al. 2012). For the availability assessment of resources consumed in a product system, including a life cycle perspective and in relation to a material inventory, the introduced scales are not meaningful.

Even though the assessment of environmental impacts of products is common practice, the linkage of environmental implications to the evaluation of resource availability is currently missing. In previous works on metal criticality, a link to the environmental implications of utilizing a particular metal are provided, but independent from the evaluation of material inventories of products. Furthermore, existing approaches provide little support for the interpretation of the results on a product-level (European Commission 2010a; Graedel et al. 2012a; Nassar et al. 2012; Nuss et al. 2014). The social dimension of resource use is widely discussed and tools (social LCA, SLCA)) (UNEP/ SETAC 2009) and several studies exist that address social impacts in the minerals industry (Azapagic 2004; GHGm 2008; Kerkow et al. 2012; Solomon et al. 2008; Tsurukawa et al. 2011). The potential effects of social circumstances on resource availability have so far not been assessed. Even though indicators for evaluating social aspects are available in the context of SLCA, the relation to resource availability is missing.

In the next section, the shortcomings of existing methods and indicators within LCA are assessed with regard to their capability to serve as a basis for determining the potential physical scarcity of resources.

1.5.2 Shortcomings of LCIA methods

In this section, the available LCIA-methods are evaluated with regard to their suitability to display potential resource scarcity. While the assessment of environmental pollution associated with resource extraction and use is common practice and the impacts of extraction as such are clearly linked to the environment, the extent to which current LCIA methods are capable of addressing resource availability is widely debated and no common understanding or methodology exist. This is mainly due to the controversial discussion of resource depletion as an environmental problem (see, e.g., Finnveden 2005; Steen 2006; Udo de Haes et al. 2002; UNEP 2010a; Weidema et al. 2005) and different perceptions of the underlying concepts of resource depletion (see discussion in Chapter 1.4). Consequently, the assessment of resource availability in LCA is shaped by a lack of consensus on methodologies and on the results of impact assessments (e.g. Berger and Finkbeiner 2011; Finnveden et al. 2009; Hauschild et al. 2013; Heijungs et al. 1997; Klinglmair et al. 2013; Lindeijer et al. 2002)).

In the context of a comprehensive evaluation of abiotic resource availability for sustainable production, not all indicators are effective and existing models are not sufficient. For assessing potential resource depletion, existing LCIA-methods exhibit several shortcomings (see i.a. Guinée et al. 2002; Klinglmair et al. 2013; Lindeijer et al. 2002):

- The environmental value of abiotic resources as such is not well defined, leading to inconsistent definitions of the underlying problem or the occurring damage.
- The reflection of and connection to depletion and potential scarcity is not straightforward.
- The informative value of LCIA-results regarding the availability of certain resources is very low, providing no decision support with regard to material choices

- Several indicators relate to the costs of resource extraction providing not a good indication of potential scarcity and lacking an environmental dimension.

Existing methods can be classified according to the underlying concepts to model resource depletion and are based on reserves or resources, exergy use, and future consequence of resource extraction. In the following these methodologies are evaluated with regard to their usefulness for addressing resource scarcity.

- *Assessment on the basis of mass*

  Mass-based indicators cover only the material resource aspect, without a direct link to scarcity (European Commission 2011c). A simple aggregation of abiotic resources on the basis of mass or energy has little informative value, as such indicators suggest that all resources "are exchangeable and equally important" (Steen 2006). Weight by itself is not a sufficient indicator for assessing the impact of resources as no relation to the potential scarcity is provided and material specific aspects (e.g., the potential for specific environmental damages) are neglected (Behrens et al. 2007). Besides, the problem with measuring things solely on a mass basis is that a lot of information is lost as environmental or economic relevance are disregarded. Based on the *material intensity per service unit* no statement can be made with regard to the effects of resource use on the environment, human health or availability of these resources in nature.

- *Assessment based on reserves and/or annual extraction rates*

  The chemical and physical basis of abiotic resources is quantifiable and availability in the earth's crust can be determined (Rankin 2011). In the CML-impact assessment, the extraction rate of a resource is divided by the reserve squared (CML 2013). The assessment of deposits and extraction rates provides information about the geologic availability and the static lifetime of deposits (Guinée and Heijungs 1995; Guinée 1995; Guinée et al. 2002; Heijungs et al. 1997). However, the definition of the recoverable deposit is a problem, as, depending on the definition of this number, results will change dramatically. It is difficult to fix convincing boundaries for the determination of resource figures as the stock size very much depends on the required effort of extraction (Goedkoop and Spriensma 2000). The EDIP 97 approach is based on economic reserves and extraction rates, but does not reflect the current importance of a resource as the global annual production drops out of the equation during the weighting of the method (European Commission 2011a; Klinglmair et al. 2013).[17]

- *Assessment based on future consequences of resource extraction*

  The extraction of high concentration resources today will affect future extraction of resources. Several methods and indicators have been proposed in this regard (Goedkoop and Spriensma 2000; Müller-Wenk 1999; Steen 1999; Steen 2006;

[17] The amount of the resource extracted is divided by the 2004 global production of the resource and weighted according to the quantity of the resources in economically-exploitable reserves (European Commission 2011a)

Weidema et al. 2005). These approaches aim at addressing the end-point/damage of resource use and are based on decreasing ore grades and additional energy requirements or costs associated with future resource extraction or with future willingness to pay.

Steen (1999) defines the estimated costs to extract and produce resources, considering different technical scenarios and assuming a very long time perspective. However, he estimates the costs of such an operation with present day technology and the present day extraction with the energy requirements that would be needed in the future (Goedkoop and Spriensma 2000; Vieira et al. 2011). Many assumptions are made and uncertainties are high (European Commission 2011a).

In the ReCiPe-method the damage to resource is defined as the additional costs society has to pay as a result of an extraction (Goedkoop et al. 2008). The method uses a monetization of surplus energy demand for characterizing future efforts for resource extraction (Klinglmair et al. 2013). Similarly, the LIME method aims at quantifying costs of the overuse of a resource (European Commission 2010b; JLCA 2012). The Eco-indicator 99 and IMPACT 2002+ assume that extraction at present will require more energy-intensive extraction in the future (Goedkoop and Spriensma 2000; Jolliet et al. 2003). The energy required for resource extraction is assumed to be inversely proportional to the ore grade. A new model developed by Vieira et al. (2012) takes a similar approach, modeling the decrease in ore grade due to an increase in metal extraction based on cumulative ore grade-tonnage relationships and also displaying increasing costs. However, modeling future consequences involves a high degree of uncertainty and estimates of future energy consumption or costs are not reliable (Lindeijer et al. 2002). Using a cost oriented problem definition of resource depletion has a direct relation to the present social context but can hardly be calculated in the long term (Steen 2006). The significance of indicators relating to costs has been challenged in previous sections of this dissertation, too.

- *Assessment based on exergy consumption or entropy production*

  Exergy is defined as the 'work potential' of a resource (Bösch et al. 2007; Dewulf et al. 2007; Dewulf et al. 2008; Finnveden and Östlund 1997; Valero et al. 2013). Exergy analysis is often perceived as a useful tool to asses natural resources as it takes into account variables such as composition, ore grade and the state of technology (Valero and Valero 2009; Valero et al. 2009). However, the exergy concept is directed at conserving exergy of ore and not of metals and the loss of exergy has no relation to the reasons why mankind is worried about the loss of resources. The exergy method is based on the inherent property of a resource. The impact pathway does not describe the depletion process, but the use of exergy. This value disregards the resource's functionality (European Commission 2011a; Heijungs et al. 1997; Lindeijer et al. 2002; Steen 2006). Methods that use the inherent property of the material as the basis for the characterization have only a low relevance with regard to expressing resource depletion, as the factor does not have a direct link to the future scarcity of resources (European Commission 2011a; Hauschild et al. 2013; Vieira et al. 2011).

The CML or EDIP 97 method are midpoint approaches, while for example Eco-indicator 99 or IMPACT2002+ include characterization factors on an endpoint level (see Table 4.3). Endpoint approaches, such as surplus energy or surplus costs, for assessing resource availability are damage oriented and depend on the societal valuation of resources rather than the physical availability as such. As endpoint approaches address the end of the cause-effect chain, more uncertainties are involved (Udo de Haes and Lindeijer 2002). Methods for assessing resource availability at the endpoint level are not well defined and still too immature to be used for modeling geophysical dimension of resource availability (European Commission 2011a; Hauschild et al. 2013). Furthermore, available methods refer to surplus costs or surplus energy, which can be questioned as an environmental endpoint as it displays an anthropocentric view and does not relate to an environmental damage but additional efforts required by society. Mid-points are problem oriented and refer to the decreasing availability of resources as such (based on reserves and/or extraction) and not the effects to society. Characterization factors on a midpoint level have high acceptance in decision making and can be regarded as relevant (Udo de Haes and Lindeijer 2002).

For assessing physical scarcity of resources, appropriate indicators need to be selected, that display the physical availability of resources in the environment in the context of maintaining natural resources. Despite existing shortcomings elaborated earlier, the abiotic depletion potential (ADP) method (Guinée et al. 2002) is recommended for example by the ILCD handbook and in the Product Environmental Footprint (PEF) as the best available practice for assessing resource depletion (on a midpoint level) (see also Dong et al. 2013; European Commission 2011a, 2013a; Guinée et al. 2002; Hauschild et al. 2013). In Box 1.4 the ADP-methodology is described in more detail.

Box 1.4: Measuring geologic depletion of resources by means of ADP

In current LCA, resource depletion is commonly assessed by means of the abiotic depletion potential (ADP), differentiation between fossil depletion and element (metals/minerals) depletion (CML 2013; Guinée 2002; van Oers et al. 2002). In the ADP model, the decrease of the resource itself is taken as the key problem (van Oers et al. 2002). The characterization factors of this method are the results of a function of the yearly extraction of a resource and the reserve of the resource (van Oers et al. 2002). The characterization factor is the ADP. This factor is derived for each extraction of elements and is a relative measure with the depletion of the element ‘antimony’ as a reference for elements and MJ for fossil fuels (van Oers et al. 2002).

To evaluate the effect of extraction on the reserve, the reserves are taken into account more than once in the ADP-method, by putting the square of the reserve in the denominator (see Equation 1) (Guinée 1995). This is done to acknowledge the fact that small stocks are a more important indicator for resources depletion than large extraction rates.

$$ADP_{i,\text{ultimate reserves}} = \frac{\text{extraction rate i}}{(\text{ultimate reserves i})^2} \times \frac{(\text{ultimate reserves antimony})^2}{\text{extraction rate antimony}} \qquad \text{(Eq.1)}$$

In this context, Guinée (1995a) proposed that for the assessment of the physical or geologic availability of resources, the reserves that can ultimately be technically extracted need to be assessed. However, Guinée argues that data on this type of reserves are not exactly known. Thus, for providing a realistic picture of resource depletion, Guinée (1995) proposed to use the *ultimate reserves* as reference. However, this figure is often criticized as *ultimate reserves* cannot be extracted completely (European Commission 2011a) (see discussion on *mineralogical barriers*, Chapter 1.4.1). Thus, developments of the ADP method propose consideration of *reserves* or *reserve base* (European Commission 2011a, 2013a). However, *reserves* or *reserve base* have a strong economic link and provide limited information with regard to geologic availability. Economic reserves and use (extraction) are co-dependent, as the search for new deposits depends on the probability of exploration and use of resources (Steen 2006). The economic *reserves* and *reserve base* of most resources have increased over the past, while the actual depletion problem (referring to the geologic availability of resources) must necessarily have increased (Guinée 1995). Reserves are affected by many factors that can change in a very short time (e.g. available technologies, resource prices). Thus, the assessment of *reserves* or *reserve base* are ephemeral (see, e.g., Kesler 2007) and are not a good basis for the assessment of the physical dimension of resource availability (see discussion in Chapter 1.4.1).

In consideration of the fact that scarcity of resources can affect human productivity a holistic and realistic assessment of resources use has to go beyond the analysis of mere (physical) availability of resources in the natural environment or the impacts of their extraction (Klinglmair et al. 2013; Weidema et al. 2005). The uneven and fixed distribution of minerals around the globe adds a dimension of risk and creates challenges of resource accessibility that go beyond purely geologic or physical considerations and gives rise to the need to involve economic, political, legal and social factors of accessibility. A comprehensive analysis towards LCSA, including social and economic information to find more sustainable means of resource use in products, is missing at the moment.

In the next section, gaps and research needs are summarized.

1.6 Gaps and research needs

To use or not to use a specific material in products needs to be evaluated by taking into account their potential scarcity. Material shortages can hinder the implementation of new technologies and can have severe effects on product systems and affect the future opportunities to use a resource. This section presents an overview of existing gaps in current resource availability assessment practices and specifies research needs that are tackled in this dissertation. In the design of products, materials are selected for their properties and for their costs and their environmental burdens. The availability and accessibility of resources is seldom considered. This is partly caused by the limited awareness, but also provoked by the limited availability of appropriate methods and models to consider resource availability during product development. Even though the debate on resource scarcity has a long history, commonly agreed indicators are not available. Furthermore, resource commonly perceived as scarce are not visible in the results of current resource assessment practice (see, e.g., *rare earths*).

Derived from the need for a comprehensive evaluation of resource availability and based on the complexity of resource scarcity outlined in previous sections, the relevant gaps in current assessments are addressed in the following list:

- **Problem definition.** Despite intensive research activities in the past, the serious difficulties in defining the “problem” of resource scarcity and the relevant *area of protection* remain. So far, resource availability has only been evaluated under the frame of environmental assessment, referring to the damages of resource extraction to the surrounding environment. Models addressing other dimensions of resource availability in the context of sustainable development are missing.
- **Physical vs. effective scarcity**. Existing approaches only address the *physical* dimension of scarcity in the context of long-term concerns. These approaches neglect the immediate link of resource availability to technological progress and human wellbeing. The availability of abiotic resources for products and product systems is not affected by the quantity of minerals included in stocks but caused by effective constraints in the supply chain of materials. Differentiation needs to be made and both dimensions of resource scarcity need to be considered.
- **Functional value.** Currently, resource availability is commonly assessed based on an evaluation of natural resource stocks. Yet the use of mineral resources does normally not mean that the resource (and its function) is lost, but rather that it is no longer available in the natural environment but in the anthroposphere. In-use stocks present another important source for materials beyond geologic stocks. This is neglected in current methods for the assessment of resource use.
- **Constraints in the supply chain.** Market induced constraints in the supply chain have been discussed before, but independently from a life cycle based approach. Social and environmental constraints to resources provision are currently neglected.
- **Implementation**. Sustainable development as such is mainly promoted at the micro-economic level. However, existing approaches for addressing supply risks refer to

organizational and national levels and cannot be linked to life cycle inventories and the evaluation of material availability on a product level. Appropriate models for a comprehensive assessment of resource availability on a product level, in the context of promoting sustainable resource use, are missing.

The models described in the previous section deliver no conclusion about actual resource availability at the production site and cannot serve as a basis for material choices. Existing methods do not come up to the standards of sustainability, enabling product development and implementation in line with considerations of inter- and intra-generational equity. Due to the complexity of resource scarcity outlined earlier, the assessment of resource availability for products solely in the context of LCA needs to be challenged. Consideration of resource availability as an environmental problem does not live up to the whole dimension of the issue. Mineral depletion is only one of several factors that threaten availability. Criteria affecting economic systems as well as potential social and environmental constraints to resource provision need to be assessed complementary to existing environmental LCA models to sustain industrial production and to increase resilience towards supply disruption.

To tackle the addressed gaps, resource availability assessment needs to go beyond evaluation in LCA and shift from assessing availability as an *environmental impact* to defining it as a *sustainability problem*. Abiotic resources need to be assessed in the context of their functional value in product systems, assessing materials with regard to current and future availability. Resource security is necessary for sustainable production and consumption. A comprehensive approach needs to be developed towards the assessment of all dimensions of sustainability in the context of LCSA.

Even though sustainability is nowadays an accepted concept, the challenge of including all three dimensions into the assessment of resource availability remains. To understand and "uncover" the constraints and risk associated with abiotic resource provision for product systems the analysis needs to go beyond the assessment of single indicators and consider the complexity of sustainable development. Sound material choices and informed product development cannot be achieved without considering both the *effective* and *absolute* availability of mineral resources. It is essential to develop a comprehensive methodology that will address risks associated with resource provision from the "triple bottom line" perspective.

To bring the comprehensive assessment of resource availability into practice an operational approach and tools are needed. Results need to be presented in an understandable yet simple and comprehensive way. Robust and easily interpretable indicators and models need to be developed that can indicate whether a particular material is potentially constrained in its supply, considering sustainability limits. Without providing numerical methods and targets for all three dimensions of resource provision capability, the sustainability concept cannot be implemented. The applicability of the models on the product-level is hereby a prerequisite. For a realistic analysis of resource availability for products, the assessment needs to enable the link to the material inventory of products and uncover high risk materials. Only such a comprehensive approach can support decision-makers in prioritizing resources for products and production processes. This can facilitate a choice of resources with more chances of positive impacts and less risk of negative ones, in decreasing the dependency on depleting and scarce resources, and in offering needed guidance for sustainable decision making.

In the next section the objective addressed in this dissertation are outlined, in the context of the identified gaps and research needs.

1.7 Objectives

In an effort to address the gaps and research needs mentioned in the previous section, this dissertation is guided by the following overall objective: *The development of methodologies for the comprehensive evaluation of resource availability considering potential physical, environmental, economic, and social constraints.*

This dissertation aims at developing a methodological framework that allows for the consideration of different aspects of scarcity to retain material security in the context of sustainable development. The comprehensive assessment constraints associated with resource provision will enable improved decision making and more informed resource management on a product level.

The consideration of additional aspects complements and broadens existing models for the analysis of resource availability in LCA, as it goes beyond an environmental function towards the comprehensive evaluation of resource availability in the context of LCSA.

Based on the overall objective and the research needs outlines in the previous section, the five sub-goals of this work are formulated. The sub-goals are the basis for the holistic approach for assessing resource availability and further highlight the methodological enhancements proposed in this work. These sub-goals comprise the following points, which are addressed in the subsequent chapters:

1. An extension of existing models for the evaluation of mineral resource depletion by including anthropogenic stocks into the assessment of physical resource scarcity (Chapter 3).
2. The determination and evaluation of economic constraints associated with the supply of materials, going beyond existing approaches and enabling an evaluation linked to material inventories of products (Chapter 4).
3. The proposal of a model for the assessment of environmental constraints to resource supply. Environmental impacts are evaluated based on existing data and impact categories within LCA (Chapter 5).
4. The development of an approach for the assessment of social constraints to resource supply based on social aspects described in social life cycle assessment (SLCA) (Chapter 6).
5. Testing and evaluation of the methods with regard to their applicability and their significance for identifying potential resource scarcity.

Ultimately, this study proposes a new framework for the assessment of potential resource scarcity by means of a comprehensive and comparative evaluation of economic, environmental and social risks in addition to physical depletion. The model can be used in connection with existing product evaluation procedures and complements current resource assessment practice as well as existing procedures. Figure 1.7 provides an overview of the scope of this thesis.

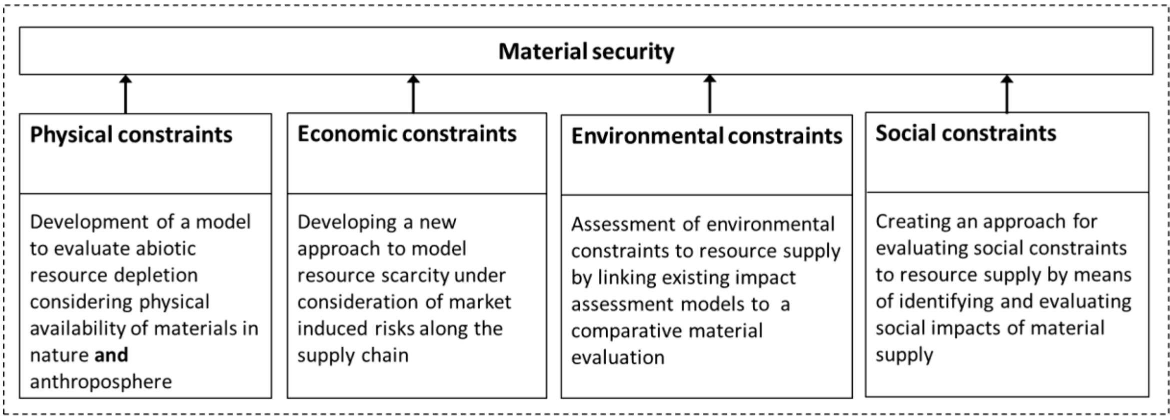

Figure 1.7: Concept for a comprehensive evaluation of abiotic resource availability

1.8 Analytical framework and delimitation

The analytical framework presented in this section serves as a guideline to set the context for this thesis and to specify the approach taken under consideration of the objective of this dissertation. The scope of this study does not extend to a consideration and revision of existing methods.

This dissertation focuses on materials, addressing the question which material is associated with the highest supply risk and subject to potential depletion. The set of models developed does not only address the effects of resource use in products on the availability of resource stocks (depletion), but also focuses on *constraints* within the *supply chain* of materials to be used in products. The analysis in this work will focus on the *resource provision level*, referring to primary material supply and focusing on the material inventory of products. Resource provision is directly linked to the product level, but instead of assessing the life cycle of products, the supply chain and stocks of abiotic resources are addressed. This classification is displayed in Figure 1.8. The use phase of products and materials is not assessed in this dissertation.

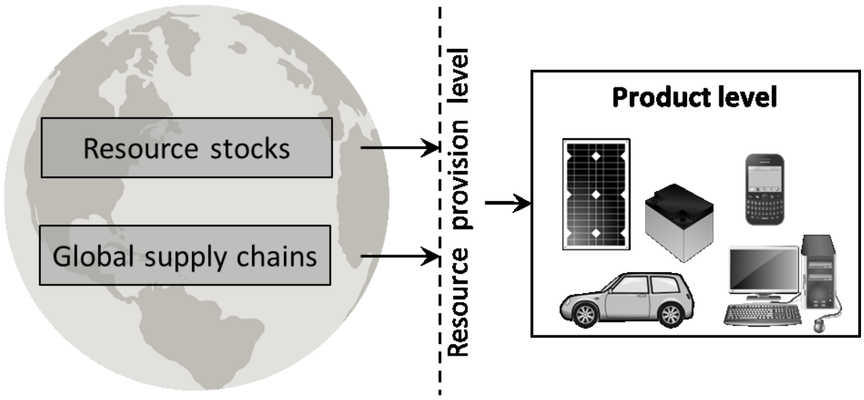

Figure 1.8: Resource provision level – Supply chains and resource stocks

The terms *resource*, *raw material* and *material* are often used synonymously, even though they denote different stages in the supply chain. Abiotic resources are extractable entities that can be found in the environment and that are useful for human purposes. *Raw materials* are resources that have been extracted due to their functional value and can either be directly consumed or transformed to serve as input to further processing stages (e.g., crude oil or iron ore). *Materials* (e.g. metals, fossil fuels) are substances (elements) with certain physical properties that are used by humans as input to production and manufacturing (Rankin 2011; UNEP 2010a). With regard to abiotic resources (as defined in this work) there is a direct link between the availability of the resource (mineral ore), the raw material and the material (metal).[18] Possible differences for the evaluation refer to the number of *supply chain stages* that need to be considered. The supply risk depends on the system under study.

In this dissertation *materials* (e.g., *copper*, *nickel*) are the focal point of the evaluation. The applied indicators ideally refer to all stages of the provision of these materials. However, following general linguistic usage and acknowledging the fact that the proposed methodologies can be applied at every stage of the supply chain this dissertation defines the underlying problem as resource scarcity (and not material scarcity).

With the term *availability* it is referred to *physical availability* of resources, as well as to the *accessibility (effective availability)* of resources.

The models developed in this dissertation are based on the common perception that abiotic resources have predominantly a *functional value* and focuses on the use value for society, excluding its non-use and intrinsic value in nature. The functionality of the resources as such is addressed, not specific functions in products.

In current environmental assessments, *potential* impacts are addressed (see, e.g., Baumann and Tillman 2004). Only potential effects are described, as little and incomplete information regarding the entire cause-impact network is available, and temporal and spatial consideration can often not be captured properly. A potential refers to a possible, as opposed to an actual, condition. Depletion (the decrease of resource stocks) is a possible consequence of resources

[18]The availability of resources is a precondition for material availability as the availability of the element (e.g., metal) as such is assessed.

use. Thus, a *depletion potential* is used to describe the *potential physical scarcity* of a resource (in line with common practice). Contrary, constraints in the supply chain are not a consequence of resource use in products but depend on the market situation and production practice. *Supply risks* associated with the material *flows* are analyzed to describe the *potential effective scarcity* of a resource. In this context the probability of the occurrence of constraints to resource supply is assessed. The effects (damages) resulting from a scarcity of certain materials are not addressed due to the high complexity and uncertainty of causal relationships. Damages would occur on a product, service or societal level and are related to the individual application and function of a material or resource. Furthermore, the identification of vulnerability of a country or corporation to supply risks or scarcity of certain resources is not part of this dissertation.

In this dissertation, the average *global* scarcity potential is defined. The depletion problem is normally considered at the global level as the geologic availability of the resources is not a function of the precise distribution of the stocks (Udo de Haes et al. 2002). Similarly, the minerals industry and supply chains are global as resources are distributed over the whole surface of the earth and are traded internationally. Supply risks will be evaluated displaying the average global situation as resource use and availability is closely related to the overall volume of economic activities and demand and the challenge of sustainability needs to be addressed as a global issue (Giljum et al. 2008; Rankin 2011). Risks associated with supply might change relatively rapidly and thus need to be reviewed on a regular basis (European Commission 2010a; National Research Council 2008).

The bottleneck with regard to the availability of certain materials may be somewhere in the supply chain. Complexity of the *supply chain* assessment of resources results in high effort for data collection and expert knowledge on every supply chain stage of the life cycle of metals. Supply chain specific information is needed as well as information regarding the inventory of products. Thus, limitations need to be made within this dissertation, which are specified in the different chapters. The dissertation does not aim at a holistic assessment of all aspects potentially constraining resource supply but focuses on the development of the methodological framework to eventually do so.

1.9 Dissertation structure

This dissertation comprises eight chapters. An introduction to the field and the presentation of the existing gaps and objectives has been given in this introductory chapter. The objectives and sub-goals of this thesis are addressed in the subsequent chapters as follows:

As a starting point, in Chapter 2 the methodological framework is defined and the relevant area of protection is detailed as a basis for the analysis of resource availability in the context of sustainability assessment. Furthermore, the basic methodological framework for assessing resource availability is outlined and the models used as a basis to quantitatively assess resource scarcity are introduced.

The following four Chapters of this dissertation introduce the different models developed in this work, focusing on the evaluation of physical, economic, environmental and social constraints to resource supply. Chapter 3 introduces an approach to extend current assessment of resource depletion including anthropogenic stocks in addition to geologic stocks. The model acknowledges the fact that the functionality of metallic resource is not lost outside the lithosphere and that anthropogenic stocks are a relevant source of materials for the future. In Chapter 4 the economic dimension of resource scarcity is addressed, evaluating the supply risk associated with marked induced constraints. In this context several aspects are proposed and evaluated to identify potential scarcity of materials. Chapter 5 describes a new model for defining and evaluating the environmental performance of materials for the identification of potential constraints to resource supply. In Chapter 6 and relevant social aspects for the mining industry are identified and a method for the determination of social supply risk for different materials is proposed. In Chapter 7 the results of the different dimensions of resource availability are evaluated. The ranking of the various materials is displayed and compared to the results of conventional resource availability assessment within LCA. In Chapter 8 the conclusions of this dissertation are presented, remaining challenges are discussed and future research needs are identified.

1.10 Publications of this dissertation

Journals

Schneider L, Berger M, Schüler-Hainsch E, Knöfel S, Ruhland K, Mosig J, Bach V, Finkbeiner M (2013) The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment. International Journal of Life Cycle Assessment 19 (3): 601-610

Schneider L, Berger M, Finkbeiner M (2011) The anthropogenic stock extended abiotic depletion potential (AADP) as a new parameterisation to model the depletion of abiotic resources. International Journal of Life Cycle Assessment 16 (9): 929-936

Book chapter

Schneider L, Berger M, Finkbeiner M (2013) Measuring resources scarcity - limited availability despite sufficient reserves. In: Mancini L, DeCamillis C, Pennington D (eds) Security of supply and scarcity or raw materials. Towards a methodological framework for sustainability assessment. European Commission, Joint Research Center, Institute for Environment and Sustainability. Publications Office of the European Union, Luxemburg, pp 32-34

Conferences and Workshops

Schneider L, Finkbeiner M (2014) Abiotic resource availability in the context of sustainability – modelling environmental, economic and social constraints, 55th LCA Discussion Forum: Abiotic resources: New impact assessment approaches in view of resource efficiency and resource criticality, April 11th, Zürich, Switzerland

Schneider L, Berger M, Finkbeiner M (2013) Resource assessment within LCA – Integration of production and consumption patterns for sustainable resource management, 7th International Society for Industrial Ecology Biennial Conference, June 25-28,Ulsan, South Korea

Schneider L, Berger M, Finkbeiner M (2013) Material assessment beyond geological availability, Proceedings of CILCA 2013 – V International Conference on Life Cycle Assessment, March 24-27, Mendoza, Argentina, ISBN 978-950-42-0146-5

Schneider L, Finkbeiner M (2012) The Long-Term Availability of Copper: A Scenario Analysis, The 10th International Conference on EcoBalance, November 21-23, Tokyo, Japan

Schneider L, Berger M, Finkbeiner M (2012) Resource availability within LCA- from geological to economic indicators, ERSCP 2012, May 2-4, Bregenz, Austria

Schneider L, Berger M, Finkbeiner M (2011) Economic material availability as a new area of protection for life cycle sustainability assessment. Paper presented at the SETAC Europe 21st Annual Meeting, 15-19 May, Milano, Italy

Berger M, Schneider L, Finkbeiner M (2011) Introducing new characterization factors for depletion of abiotic resources: anthropogenic stock extended abiotic depletion potential, CILCA 2011 – IV International Conference on Life Cycle Assessment, April 4-6, Coatzacoalcos, Mexico

Berger M, Schneider L, Finkbeiner M (2010) A New Characterization Model for Depletion of Abiotic Resources – The Anthropogenic Stock Extended Abiotic Depletion Potential, The 9th International Conference on EcoBalance, November 9-12, Tokyo, Japan

2 METHODOLOGICAL APPROACH

Abstract

Abiotic resources are essential for the functioning of societies and maintaining natural resource stocks and securing continued supply is a goal of sustainable development. But how can we evaluate whether materials will be available? The objective pursued in this chapter is the development of a comprehensive approach for assessing potential resource scarcity, oriented on the requirements and dimensions of sustainable development.

Firstly, the definition of the area of protection (AoP) with regard to abiotic resources is revisited and an extension towards sustainability assessment is proposed. "Resource provision capability for human welfare" is identified as an apt description of the general concern over the access to resources and the availability for human use now or in the future. For applying the AoP in the context of sustainability assessment, implementation needs to go beyond the current environmental focus and include a comprehensive assessment of potential constraints to resource supply. Secondly, the methodological framework proposed in this dissertation to integrate the different aspects of scarcity into the analysis of resource availability is outlined in this chapter. The assessment of resource availability needs to reflect the complexity of sustainable development. Physical and effective scarcity have to be addressed by means of different principles and models. A further differentiation between the underlying problem definition and the cause-effect-relation is made as a basis for apt methodological development. While the future availability of resource is related to resource stocks and current consumption, availability for today's need is related to constraints in the supply chain of resources. Different methodological approaches are needed for addressing these issues.

For assessing resource stocks and their potential depletion, this dissertation relies on existing approaches and logic within LCA, but proposes a new parameterization of available methodology, accounting for the functional value of resources. The assessment of supply risks is linked to an evaluation of the contribution of individual constraints and will be based on a distance-to-target approach. Living up to the expectations of sustainable development, the model addresses direct and indirect constraints in the supply chain and will help to identify bottlenecks that can affect resource supply.

The developed models will complement current resource availability assessment and outline a way to capture and integrate potential constraints to resource provision capability into product evaluations. Thus, a more comprehensive picture of resource availability in the context of sustainable development can be provided.

2.1 Abiotic resources and the relevant area of protection

As a basis for the development of appropriate models for assessing resource availability two questions need to be answered: *What is the core problem? And what needs to be protected?* The previous chapter provided an overview of existing models to evaluate resources use and availability and the need for a more comprehensive assessment was outlined. Hence, this chapter focuses on the extension of current resource assessment practice by developing a methodological framework to account for constraints to resource availability from a holistic perspective. As a first step, the definition of the area of protection (AoP) in LCA is revisited and defined more comprehensively for the application in the context of LCSA.

The term AoP is used to express what is of value to human society and what needs to be sustained (see, e.g., Dreyer et al. 2006). In LCA resources and their availability in nature are the focal point of assessment. The AoP "natural resources" relates to the use of natural resources with implications for their present, but mainly future availability (see, e.g., Lindeijer et al. 2002). The availability of natural resource stocks is identified as the main concern. However, this is only part of the truth. Resource availability has a clear link to technological progress and human wellbeing today. The general concern with regard to resources is a shortage in supply relative to the interests and needs of humans and not only the geologic availability (see also DeYoung Jr. et al. 1987; Mancini et al. 2013). The link of resource availability to the needs of human society has been established before. However, so far these topics have only been addressed under the frame of environmental assessment. The definition of existing AoPs does not originate from a discussion of the societal value of resources (see, e.g., Dreyer et al. 2006).

A comprehensive approach and a clear definition of the problem in the context of sustainable production and consumption and acknowledging the complex relation of resource availability to human wellbeing are still missing. For achieving sustainable development the sustained provision of resources for current and future generation was identified as the key concern (see, e.g., Brentrup et al. 2002b; European Commission 2010c; Hauschild et al. 2013; Klinglmair et al. 2013). Acknowledging the definition of natural resources according to their usefulness for human purposes, the United Nations Environment Programme specified the "resource provision capability for human welfare" as the correct description of the AoP currently addressed in LCA (see Lindeijer et al. 2002; UNEP 2010a; Wehmeier et al. 2005). This definition already goes beyond a direct link to environmental consequences of abiotic resource use. In fact, *resource provision capability for human welfare* is already aptly describing the general concern over the access to resources and the availability for human use. Thus, this work takes up the existing definition of the AoP, but proposes an extension of the focal point towards sustainability assessment. Resource provision is not only a depletion problem, but a sustainability problem including concerns with regard to inter-generational material security and intra-generational supply security. In the context of achieving sustainable development, the amount of material available to society (now or in the future) is influenced by physical realities, politics, economic circumstances and social or environmental performance. The evaluation of resource provision capability thus needs to focus on implications of resource use for future generations and accessibility of resource for current generations.

The provision of sufficient amounts of abiotic resources as such needs to be protected to sustain today's economic activity and also to secure the availability of resources for potential future needs. Hence, the causal relationship between scarcity and the various levels of consequences need to be considered rather than damages. The actual damage of depletion and supply risks on a product, service or finally societal level can hardly be quantified as

- effects occur well into the future and need to consider future circumstances to determine the actual damage, and
- supply risks are relative and not absolute and the potential damage depends on several factors (vulnerability of companies, product specific application etc.) that cannot be determined.

Hence, the potential damage of resource scarcity is disregarded in this work.

In the next sections the key constraints of resource provision capability are defined and assigned to the framework of sustainability. The cause-effect relation of the different constraints is addressed and the basic methodology is outlined.

2.2 Methodological framework for assessing resource provision capability

For protecting resource provision capability, the potential of resources to fulfill their desired function in current products and the continuity of resource use over a long time period need to be considered. This section gives an overview of the methodological framework to address the different notions of resource availability as defined in this work. The distinction between physical and effective scarcity are taken up in this section and are further defined for the development of a comprehensive approach. The concept of sustainability provides the framework for the methodological approach in this dissertation.

Following the definition of scarcity in Chapter 1, the assessment of resource provision capability needs to be differentiated into two general problems: *physical* and *effective scarcity.* In Table 2.1 a summary of the characteristics of these two notions of scarcity is provided. The methodological framework developed in this dissertation needs to reflect these characteristics, and differentiate between an assessment of the *consequences* of resource use in products today (depletion) and the *effects* of constraints in the supply chain (supply risks) on current resource availability. While supply risks are independent from the quantity of resources used, the extent to which the use of a resource in products contributes to its depletion depends on the amount and the way the resource is used.

Table 2.1: Physical and effective scarcity – An overview

Physical scarcity		Effective scarcity
Problem: Depletion	⟷	Problem: Supply risk
Focus: Future generations	⟷	Focus: Current generations
Consequence of resource use today	⟷	**Effect on** resource availability today
Scope: resource stock	⟷	Scope: resource flows

When addressing resource availability in the context of sustainable development, availability for current as well as future generations needs to be addressed. While constraints in the supply chain and potential effective scarcity are of concern for current generations, the functionality provided by resources as such is of importance in the long term. The future supply of resource cannot be defined and resource provision capability needs to be assessed rather in the context of potential limits to the opportunities for future generations to use certain resources.[19]

Thus, focus for the assessment of future resource availability is not on the flows of resources and potential supply risks, but on any potential decrease of the physical stock. The long term availability of resource will be addressed independent of supply chain consideration.

Focus of this dissertation is on the *resource provision level* (see also Chapter 1.8).[20] Resource provision capability for product systems and potential constraints need to be evaluated. For the assessment of the physical dimension of resource scarcity the contribution to depletion is assessed focusing on the development of resource availability over lengthy time periods. In this context the consequences of resource use for the magnitude of the resource stock need to be assessed (see also Lindeijer et al. 2002). Supply risks associated with resource use do not depend on a specific product, but on the demand for resources as such and on the overall market situation. In this context an average approach is used, providing information of the average global supply associated with different materials. System boundaries ideally should encompass all stages associated with the provision of resources as risks can occur at any stage of the supply chain. Currently, the product is in the focus of most assessments and choices are made on a product instead of a resource provision level disregarding potential constraints in resource supply. However for sustainable production and consumption the functions that resources provide need to be secured and resource provision capability needs to be addressed rather than effects of resource use on a product or service level (addressing impacts of resource use). The underlying causal relationship is specified in Figure 2.1.

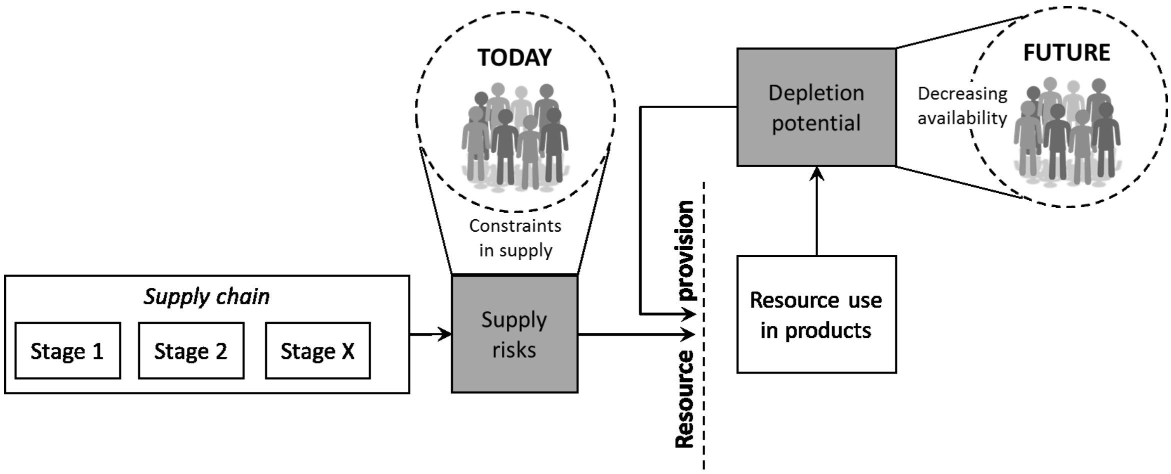

Figure 2.1: Structure of the analyzed system – Depletion and supply risks

[19]Although it is impossible to predict material needs of the future and to foresee future supply new products will certainly rely on chemical elements and minerals that are finite and in limited supply and opportunities to use resource need to be protected.

[20]Resource provision can hereby refer to any stage of the supply chain and can encompass the provision of materials or raw materials, depending on the definition of the assessed system.

This dissertation addresses different dimensions: physical constraints, environmental constraints, economic constraints, and social constraints (see Figure 2.2). For the determination of the four levels, the concept of sustainability is taken as a basis and the opportunities to use resources in current and future generations are evaluated. While current resource assessment in LCA (see Chapter 1) addresses the geologic availability of resources under the umbrella of environmental assessment, environmental and physical constraints are treated as two separate aspects in this work.

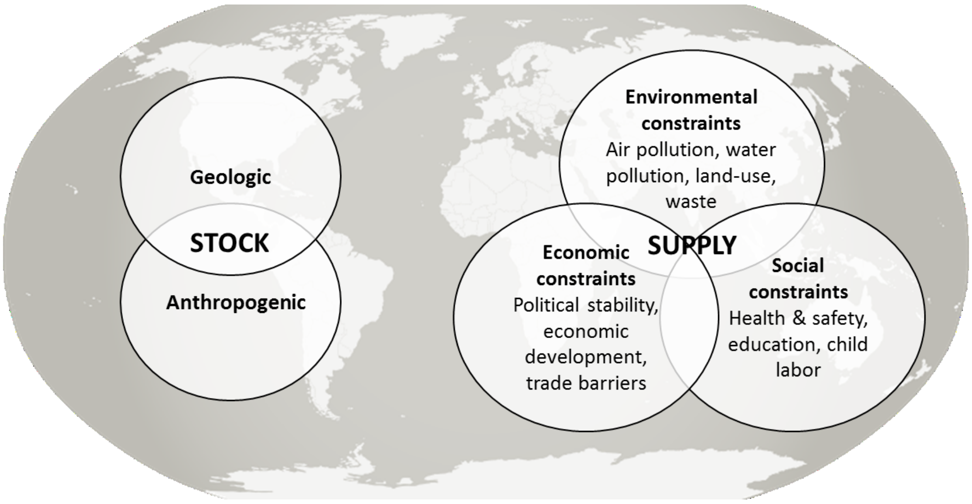

Figure 2.2: Dimensions affecting resource provision capability

Supply may be effectively constrained by economic, social or environmental factors. Economic risks can occur at any stage of the supply chain for the provision of resources and are normally caused by geopolitical factors or market structure (and are associated for example with countries or technologies). From the social perspective, company behavior or specific situations in countries or sectors determine the average social risks. Contrary, from an environmental perspective, process specifications are of relevance. The way the different dimensions affect resource provision capability is based on two fundamental principles. Abiotic resource provision capability is directly constrained by

- available stocks of resources (either in the earth's crust or the anthroposphere) and
- constraints in the supply of materials associated with geopolitical, market or political issues.

Furthermore, resource availability can be indirectly constrained by

- environmental pollution caused by mining activities (e.g. due to increasing amounts of energy consumed) and
- negative societal impacts during the extraction and processing of resources and materials.

Direct constraints are those constraints that directly affect the availability of materials at the level of resource provision and refer to interruptions in the supply chain or the decreased availability or rarity of an element due to depletion. Indirect constraints occur also in the supply chain of materials, but are not caused by supply chain interruption as such but are induced by concerns over ecosystem health or human wellbeing. Resource provision can be indirectly constrained as measures can be taken with the intention of protection the environment or the society. Many companies measure and evaluate activities with regard to their contribution to sustainable development. Concerns over the performance of products in context of for example customer requirements or growing community expectations (societal level) can lead to constraints regarding the material choices of companies. Indirect constraints can occur at a consumer, at a corporate or at a political level, referring either to limited consumer acceptance, violations of corporate social responsibility (CSR) goals or legislations or laws that constrain the supply of resources in the context of environmental goals, etc. The constraints originate in the concern over potential damages to human wellbeing, human health or ecosystems. The risk of violations of governmental guidance or non-compliance with stakeholder demands occur at every stage of the supply chain and can lead to *immediate* constraints in production (e.g., adoption of environmental limits with regard to the mining of specific materials that will constrain the supply of resources as such) or *retrospective* constraints caused for example by concerns over the environmental performance of a product, but beyond the actual resource provision stage (e.g., product level or societal level). This is important, as it goes beyond individual supply chain stages, and can occur at a level beyond the resource provision level as such (and thus indirectly). In Figure 2.3 this relation is clarified. Material choices need to comply with corporate, governmental and societal goals and principles.

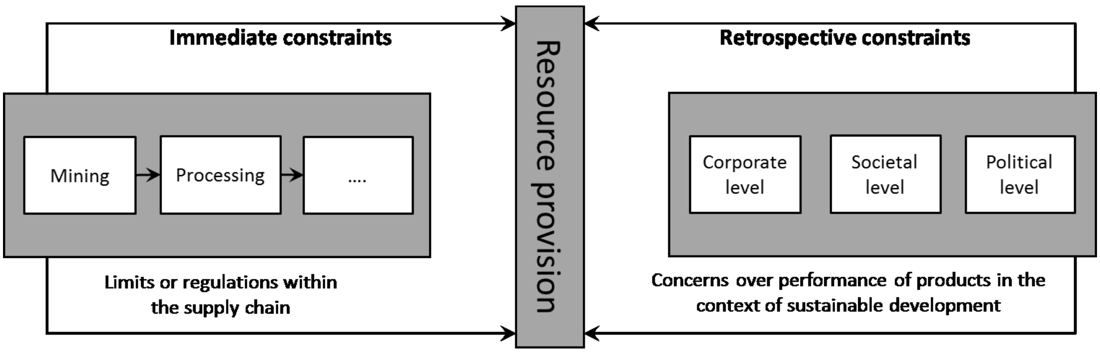

Figure 2.3: Indirect constraints to resource supply –Immediate or retrospective effects

Even though it might be perceived that for example societal values are not strong enough to bring about changes in the way of life (e.g. most people will not be willing to give up their car, TV, or similar), products that are developed socially responsible and with decreased environmental impacts are becoming increasingly popular and relevant in the context of sustainability goals. Thus, the consideration of such factors becomes more and more important and gains increasing influence in product development.

In Figure 2.4 the multiple cause-effect relations of resource utilization are displayed as assessed in this work (indirect constraints are hereby displayed by dashed lines). Sound material choices can only be made if, in addition to physical constraints, environmental, economic and social constraints are considered for the evaluation of resource provision capability.

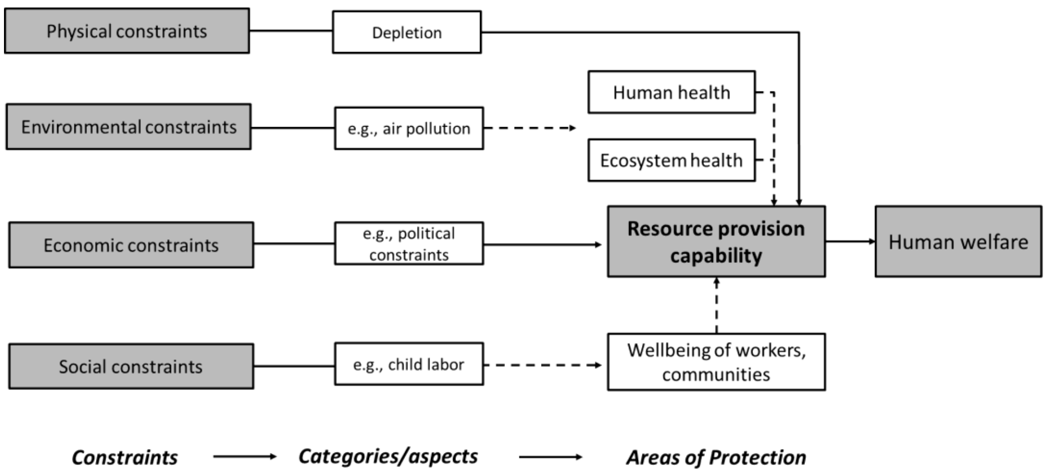

Figure 2.4: Constraints and link to resource provision capability – Cause-effect-network

For assessing the potential resource scarcity, the different dimensions affecting resource provision need to be transferred into quantifiable and robust models that can be linked to decision making procedures on a product level. The basic methodology applied for the assessment of the different constraints to resource provision is introduced in the next section.

2.3 Characterization methods

This section introduces the methodological framework used for addressing the different dimensions of resource scarcity. The methodologies developed in this dissertation build upon existing practices and data. The different parts of the model are all based on the well-established environmental LCA framework (Finkbeiner et al. 2006; ISO 14040 2006; ISO 14044 2006; Klöpffer 2008) and provide a basis for the assessment of resource use and availability in the context of LCSA. However the models proposed in this dissertation focus not on the entire product life cycle but on the relevant stages of resource provision only. A close reference to the underlying terminology and logic of LCA makes sense to facilitate easy implementation and application.

As a first step, models need to be developed to define the relation from the cause (constraints) to the effect (potential resource scarcity). In current LCA practice, environmental problems are linked to consequences via environmental characterization models. In a characterization step the relative contributions of the resource consumption to abiotic depletion are calculated. Current characterization modelling in LCA is, for example, based on the geologic occurrence of resources and considers the size of reserves and extraction rates.

For evaluating resource availability in the context of LCSA, new cause-effect chains have to be identified and "characterized". Hereby, the cause-effect networks can be outside of the environmental system, and include economic or social relations. The characterization in this work does thus not necessarily relate to an environmental mechanism as such, but refers to the linking of a certain aspect or indicator to the potential consequence (e.g., supply risk) in general. As the basis for the methodologies developed in this dissertation, possible cause-effect-pathways and suitable indicators are developed and identified. In line with the framework outlined in the previous section, following notions need to be considered:

- The physical availability of resource needs to be based on stocks and extraction to depict the decreasing availability for future generations (depletion)
- The supply risk associated with different resources needs to be evaluated under consideration of potential environmental, economic and social constraints

For the assessment of resource availability for future generations, the decrease of the resource itself is deemed the key problem in this dissertation. This is in line with current understanding of the resource problem in LCA. Thus, to address the physical availability of resources, this dissertation takes up and complements existing characterization models and cause-effect chains in LCA. Existing characterization models in LCA assess the geologic scarcity of material based on the extraction rate compared to the available stocks in the earth's crust. The mechanism applied is as such well-suited for assessing resource depletion and is perceived as a good starting basis for the assessment of physical scarcity. However, in the context of the functional rather than environmental value of abiotic resources, resource stocks in the anthroposphere need to be addressed in addition to geologic stocks and a new parameterization needs to be developed (see Chapter 3).

The definition of supply risk is a relative rather than an absolute concept. Evaluation of risk has a high degree of subjectivity (system specific perspective) and can change depending on the geographical and temporal reference (Arrow 1965). Analysis and interpretation of risk can be orientated on an objective understanding of risk, but ultimately determination of risk depends on the system and relates to the systems area of procurement. The perception of risk, the focus of the study the function of a material and its relevance, the time scale and the perspective of the assessment can influence the evaluation and results.

When evaluating economic, environmental or social information in the context of their effects on resource supply, a measure to quantify the contribution of individual constraints to the supply risk needs to be determined by means of a characterization step. However, for assessing supply risks, characterization models need to involve additional information on thresholds or targets to determine when a certain situation might become a risk. Hence, to create this link, it is proposed to use a similar formula as specified in the ecological scarcity method (a 'distance-to-target' method) to include a threshold or "scale of risk" into the evaluation of the different constraints (Frischknecht et al. 2009; Hischier and Weidema 2010; Müller-Wenk 1978) (see Eq. 2). The resulting factors enable an identification of the materials at risk and depict the potential impact on the overall supply risk of a resource. Theses impact factors (I) are a function of current indicator values and the threshold above which high risk of supply is expected. The definition of the thresholds depends on value choices and needs to be interpreted in the respective context. The actual value can either refer to indicators or to any measure used to describe the actual situation in the context of the question asked. The target can refer to internationally set thresholds, or individual goals according to a general perception and best practices. The assessment of supply risk has to be seen in the context of a concrete situation (product systems) and the specific perception of the risk. Thus an individual determination of the thresholds should be allowed for the identification of supply risks.

Impact factors will be calculated for each resource (i) and each constraint (j). For calculation of the impact factors the ratio of the current to the critical flow is squared: this means the major exceeding of the target value (implying high risks) is weighted above-proportional (Frischknecht et al. 2009). For an evaluation in the context of LCSA, introduced scales need to represent a significant margin, so that results would not be influenced by the amount of the materials used in products but by the respective supply risk (see also identified gaps). Any position above the threshold represents a risk, with higher values determining a higher degree of risk.

$$\mathrm{I}_{\mathrm{i,j}} = Max\left\{\left(\frac{\text{actual value}_{\mathrm{i,j}}}{\text{threshold}_{\mathrm{i,j}}}\right)^2 ;1\right\} \qquad \text{(Eq. 2)}$$

The different impact factors can, in a next step, be aggregated to a single "resource scarcity potential" to enable easy ranking and comparison of the risks associated with different materials. The determined indicator results are a function of the (aggregated) impact factors and the inventory of a material. In this context, when linked to a product inventory, an indication about the magnitude of the risk associated with different materials shall be provided. The amount of a specific resource used is important for determining the impact of resource scarcity on a company level, but not for the determination of the risk probability as such. To reinforce identified risks multiplication is used during the aggregation step. As this model will be linked with inventory data that might be dominated by few resources, impact factors need to have a significant range, so results are not determined only by the specific quantity of resources used.

To display the overall supply risk, compensation during further aggregation of impact factors needs to be avoided. Thus, no values below "1" are permitted in the assessment (see Eq. 2). Resulting (aggregated) supply risk associated with resources is a dimensionless quantity determined exclusively by the ratio of the current indicator value to the determined threshold linked to the life cycle inventory (LCI) (see also Frischknecht et al. 2009).

While there is controversial discussion about the application of weighting within LCA, a weighting step is undertaken at the characterization level in this dissertation (see also UNEP/ SETAC 2009). In the here assessed context regarding the analysis of supply risk of resources independently from LCA, the applied method is feasible.[21] In Table 2.2 the basic parameters of the methodological approach in this work are outlined, summarizing the characteristics defined in this chapter.

[21] Aggregation, used in this work will use equal weighting of individual impact factors. This approach can of course be modified as weighting might prove useful for emphasizing individual aspects.

Table 2.2: Basic parameters and approach outlined in the methodological framework

Parameter	Approach
AoP	*Resource provision capability for human welfare* is defined as a separate AoP covering all dimensions of sustainability ⟶ resource provision capability needs to be protected, beyond an environmental scope
Inventory	Evaluation of material inventories of products but with focus on resource provision level, considering constraints to resource supply and decreasing stocks
Cause-effect relation	Physical and effective scarcity need to be addressed ⟶ supply risks and depletion are evaluated, acknowledging the different cause-effect relations - Use of resources in product systems causes depletion – effects of resource use on depletion need to be addressed - Constraints in the supply chain have effects on resource provision capability
Characterization	Consideration of anthropogenic and geologic resource stocks ⟶ new parameterization of existing characterization models to assess resource depletion in LCA
	Introducing risk-thresholds to determine supply risks ⟶ consideration of all three dimensions of sustainability
	Focus of the assessment is on potential constraints (negative impacts)
Interpretation	Comparative analysis, no absolute but relative results are the basis for the interpretation of potential resource scarcity
	Physical and effective scarcity are treated as two separate concerns
	Different dimensions of supply risks are equally relevant and no ranking is applied

The methodology is transparent and can be used to assess hotspots and bottlenecks along the supply chain of materials. Furthermore, the relative contribution of the different constraints can be uncovered, facilitating interpretation and decision making. However, it has to be kept in mind that the results are highly dependent on the definition of the threshold the definition of the system under study. In this dissertation, a global perspective is taken and the average global risk will be addressed.

As an outcome of the framework detailed in this section several methodologies are proposed in this dissertation to comprehensively address resource availability:

1. The **anthropogenic stock extended abiotic depletion potential** (AADP) for assessing physical resource provision capability beyond geologic stocks (Chapter 3)
2. The **economic resource scarcity potential** (ESP) for assessing market risks (economic risks) within the supply chain of materials (Chapter 4)
3. The **environmental resource scarcity potentia**l (EnSP) for determining potential constraints caused by the environmental impacts associated with resource production (Chapter 5)
4. The **social resource scarcity potential** (SSP) for assessing potential constraints to resource supply induced by social impacts during resource provision (Chapter 6)

Only the potential impacts on resource availability are assessed, as the real impacts in the future cannot be determined with a high degree of certainty and the value of resources depends for example on the level of development of the society and future products. The analysis can be conducted in connection with existing LCA procedures and in line with current resource assessment practice and facilitates easy implementation on an organizational level. While LCA and SLCA methods and databases are used as a basis for the assessment of the physical, environmental and social dimension, the economic dimension will be addressed independently from other tools (see also discussion outlined in Box 1.3).

In Figure 2.5 an overview of the structure of this dissertation is provide. The cause-effect-relation is shown with regard to the four aspects of resource scarcity considered in this dissertation and their evaluation within this work is outlined.

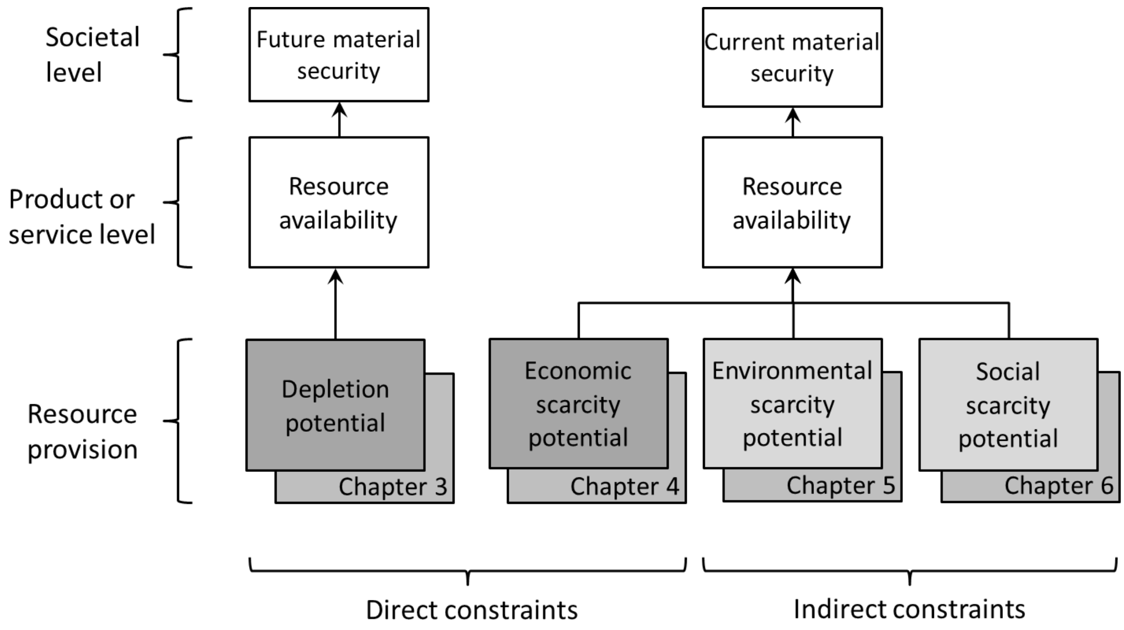

Figure 2.5: Overview and structure of dissertation

Addressing only one dimension of resource availability does not provide all the information needed to make decisions in a sustainability perspective. The proposed models will provide the basis for a comprehensive framework for the analysis of resource provision capability.

3 NEW PARAMETERIZATION TO MODEL THE DEPLETION OF ABIOTIC RESOURCES

Abstract

All indicators presently available for assessing resource depletion share a shortcoming as they neglect the fact that large amounts of raw materials can be stored in material cycles within the technosphere. These "anthropogenic stocks" represent a significant source of materials and can change the overall availability of resources.

As a sub-goal of this dissertation, a new parameterization to model the depletion of abiotic resources is introduced; the anthropogenic stock extended abiotic depletion potential (AADP). The underlying characterization model is based on the ADP model that is recommended as current best practice for assessing resource availability in LCA. The proposed model considers anthropogenic stocks in addition to lithospheric stocks and enables an assessment of physical resource availability beyond geologic finiteness. Furthermore, the new model reconsiders the definition of geologic resource stocks and aims towards the assessment of the ultimately extractable amount of resources rather than average concentration in the earth's crust or economic measures.

With the new characterization factors resource consumption is assessed by acknowledging the functional value of mineral resources. The developed approach is a relevant enhancement towards sustainable development, as not the extraction of resources as such is evaluated as of concern but rather their dissipative use and loss. A comparison between AADP and ADP reveals different results. The results confirm that materials with high anthropogenic stocks are comparatively less critical than materials with low anthropogenic stocks. Thus, the new characterization model can enable a more realistic assessment of physical resource provision capability beyond the currently established evaluation in LCA.

This chapter is based on a publication in the International Journal of Life Cycle Assessment but contains additional aspects and discussion on this topic.

Published as: Schneider L, Berger M, Finkbeiner M (2011) The anthropogenic stock extended abiotic depletion potential (AADP) as a new parameterization to model the depletion of abiotic resources. International Journal of Life Cycle Assessment 16 (9):929-936

3.1 Scope

Gerst and Graedel (2008) point out that the continued increase in the use of metals over the 20th century has led to the phenomenon of a shift in metal stocks from the lithosphere to the anthroposphere. As resources are depleted only when they leave the economy in a form that functionality can no longer be restored (Stewart and Weidema 2005), these "anthropogenic stocks" represent a significant source (Brunner and Rechberger 2004; Kapur and Graedel

2006). The anthropogenic stock will become available in the future for recycling and reuse and have to be acknowledged when assessing the future resource availability or the depletion potential of a material. Yet, so far all existing indicators neglect the fact that large amounts of raw materials are stored in material cycles within the anthroposphere.

Depletion can lead to the *absolute scarcity* of resources (see Chapter 1.1.2). As mineral resources have mainly a functional value, the availability of the potential to fulfill functions for society determines the overall availability of a resource. By focusing only on the yearly extraction of natural resource in relation to the available geologic stocks, the depletion of resources is overestimated (van Oers et al. 2002). While many materials are consumed, meaning that they get used up, metals are used only, as their functional, elementary properties are not lost through use. In fact, the function is still available when the materials are employed in products and also during the end-of- life phase of products. For metals the element as such is relevant for fulfilling a function. As the element is not changed during use it is (in theory) still available for future use. For fossil fuels, the specific chemical compound matters for fulfilling the desired function (Guinée 1995). Thus, contrary to metals, fossil fuels are used up for producing products and changes the initial structure (e.g., fossil fuels are burned for producing energy, or are transformed to a different status like plastics). To what extent for example plastics can still be used to provide the initial function of fossil fuels is up for discussion and needs closer examination.

The basic question in the context of sustainable development should not be ‘how much primary material is extracted?’, but rather ‘how much material is dissipated?’. This is in line with the goal to preserve the function of an abiotic resource rather than availability in nature.

In the next section, classification and characteristics of anthropogenic stocks are outlined and the evaluation in the context of this dissertation is described.

3.2 Anthropogenic stocks and dissipation

Anthropogenic stocks refer to the amount of stock present in the anthroposphere. While geologic stocks are recovered by means of extraction, anthropogenic stocks are recovered by means of recycling and reuse. Metals can be “renewable” if properly managed (recycling) (UNEP 2010a). Thus, not the extraction of metallic minerals from the environment is of concern, but rather the dissipative use and disposal of materials (Stewart and Weidema 2005).

When referring to the anthropogenic stock metals can be present in different states and conditions which give an indication about the actual availability of the material. Figure 3.1 (left) displays the different types of geologic and anthropogenic stocks, complementing Figure 1.5 in Chapter 1. Employed stock is the amount represented in the anthroposphere that is still in use and not yet discarded while hibernating stock represent the amount of resource that is not used anymore, but which has not been discarded yet, either. Expended stock is the total amount of resource that has been discarded. Thereby, the deposited stock is the amount of the resource that has been deposited, in for example landfills, and the dissipated stock is the amount of a resource that has been returned to nature in a form that makes recovery almost impossible (Gordon et al. 2006; Kapur and Graedel 2006). Furthermore, the material cycle from lithosphere to anthroposphere is displayed (Figure 3.1 (right)).

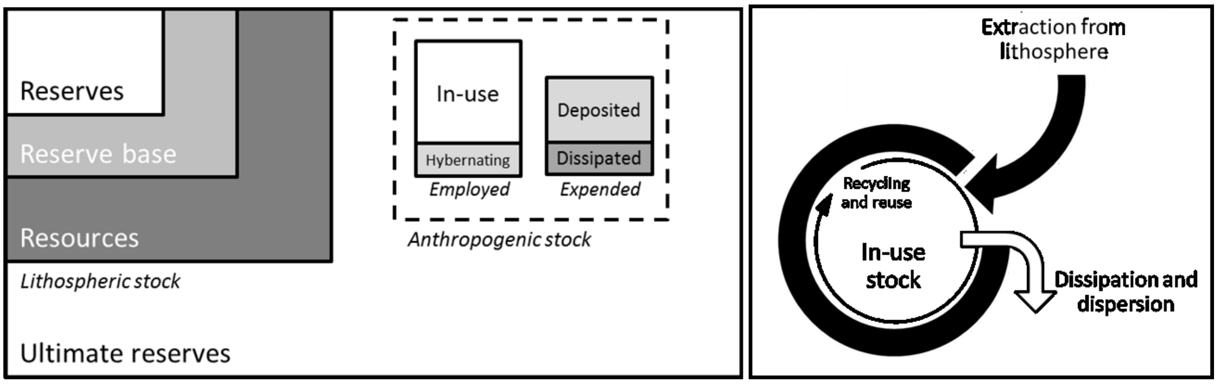

Figure 3.1: Types of anthropogenic stocks (left) (based on Kapur and Graedel 2006) **and the material cycle** (right)

Currently, data for anthropogenic stocks generated through the analysis of materials flows is available for a limited number of materials only (UNEP 2010b). For this reason, anthropogenic stocks in this work were determined as the accumulated extraction rate since the beginning of records, in approximately 1900, until 2008 based on data from the U.S. Geological Survey (USGS 2010a). It is assumed that the amount of materials mined before is negligibly low in comparison to the large volumes and rates extracted since 1900. The material is present in the anthroposphere as either *in-use*, *hibernating*, or *deposited stock*. Hence, the total mass of one metal in society, regardless of its chemical form, is included in the assessment of the anthropogenic stock (UNEP 2010b). It should however be noted that the some of the metal in the anthroposphere is used in a form that leads to physical disintegration or dissipation. Dissipation or dispersion of materials occurs, for example, in the case of corrosion of surfaces exposed to weather, during the use phase by abrasion or diffusion (as for the case of platinum used in automotive catalysts), during production (e.g., losses to residues or tailings), or in inherently dissipative applications such as *titanium* in spraying paints or *platinum* used in very thin layers in hard disc drives (Graedel et al. 2014; Hagelüken 2005; Kapur and Graedel 2006; UNEP 2010a; Wäger et al. 2011). Furthermore, certain materials can dissipate due to mixing of alloy elements (Vieira et al. 2011). The *dissipated stock* should be subtracted from the total anthropogenic stock in the calculation as the future recovery of dispersed and dissipated products is impossible.

Dissipation decreases the future availability of metals as potential functions will be lost for societal use (van Oers et al. 2002). Thus, the assessment of the anthropogenic stock is a good measure of how sustainable the use of the material is (relating to low rates of dissipation) and provides a good indication with regard to the future possibility to rely on recycling rather than on virgin ore for providing materials for product systems.

Detailed material flow analysis of *copper* has shown that the *dissipated stock* accounts for less than 1 % (Kapur and Graedel 2006). However, it has to be acknowledged that materials have different characteristics that influence the amount of dissipation. Metals are easier to recover from certain scraps than from others. Inappropriate material combinations and low alloy concentration can drastically impede the technical and economic recoverability of materials

(Reuter et al. 2005; Wäger and Classen 2006). The recovery of materials from anthropogenic stocks is further limited by their high entropy states and unknown disposal (Wolfensberger et al. 2007). Those issues are not considered further in this work, as of the time being. Furthermore, no differentiation is made between anthropogenic stocks that are available for immediate application or that are currently 'fixed' to some product. As physical resource stocks are assessed from a longer-term perspective in this dissertation such a distinction is not made (in line with the definition of geologic resource stocks, see Chapter 3.3). Contrary to metals that have a function on the elementary level, and can thus build up significant anthropogenic stocks, stocks of fossil fuels are more complicated to assess. The function of fossil fuels is mainly to supply energy. During this process, fossil fuels are burned, and the compound as such and its functions are lost. Yet, mineral oil is not only used as energy carrier, but also as raw material for the production of plastics and bitumen (van Oers et al. 2002). To what extent these materials can be considered as anthropogenic stocks of fossil fuels (delivering the same function of providing energy) would encompass consideration of the chemical state and efficiency loss and is not further addressed in this work. In this work, for the time being, only metallic elements are considered.

In the next section, the methodology proposed in this dissertation, for including the anthropogenic stocks into the assessment of resource depletion is described.

3.3 Methodology

The availability of anthropogenic stocks determines the potential for recycling, and further use of those stocks. The availability of anthropogenic stocks has an important relevance with regard to the physical availability and potential depletion of materials. This section specific the methodology proposed in this work to include anthropogenic stocks into the assessment of resource depletion.

3.3.1 System description

In this section the development of the new parameterization of the characterization model is described more closely. Hereby, the ADP model which is currently applied within LCA for the assessment of resource depletion is used as a basis.

The adaptation of existing characterization factors will be conducted in two steps: The first step refers to an adjustment of the lithospheric stock considered for the assessment of material depletion (discussed below) and the second step is the inclusion of the anthropogenic stock into the characterization model.

Within the current ADP model (Guinée et al. 2001) the total amount of a material in the earth's crust is used. However, these *ultimate reserves* are not a good indicator to measure resource scarcity as they will never actually be possible to exploit (Müller-Wenk 1999; Tilton and Lagos 2007) and cannot reflect shortages. Any material will eventually deplete, even if lower and lower grade ores are included in the extraction, as costs and impacts will become too high (Steen 2006).

Adjustments of the conventional model have been proposed before. According to Brentrup et al. (2002) only *reserves* should be used. Guinée et al. (2002) and van Oers et al. (2002) already proposed to use the *economic reserves* instead of the *ultimate reserves* in an alternative characterization model. Yet, these economic *reserves* and also the *reserve base* are actually not directly related to the depletion problem, as noted by Guinée (1995), but more an economic parameter, subject to constant change as directly dependent on the price of a material. A valid, long-term assessment of resource availability has to acknowledge the relevance of technical improvements. When providing the conventional ADP characterization model, Guinée (1995) already pointed out that rather the consideration of the *ultimately extractable reserve* would be the relevant parameter with regard to depletion. However, data on this type of reserve are hard to find and will never be exactly known because of their dependence on many parameters like future technological developments (see discussion provided in Chapter 1, Box 1.4).

For the assessment of physical resource availability, the theoretical extractable amount for society has to be assessed. In this study determination of the anthropogenic stock, as described in the previous section, is based on the theoretical available amount in society (disregarding the dissipated stock), having a strong link to the future availability of resources. As discussed by Guinée (1995) and van Oers et al. (2002), also the determination of geological availability should be oriented on the ultimately extractable amount of a resource. However, as pointed out before, these geological reserves are hard to detect and hence an approximation has to be used. As the consistency of anthropogenic stocks and reserve figure used is of importance, geological reserves for this study are best described with *resources* (according to the U.S. Geological Survey (USGS 2014b). *Resources* are by definition located between *reserve base* and *ultimate reserves*, and thus closest to the definition of *ultimately extractable reserves* (Guinée 1995; van Oers et al. 2002). *Resources* include material that cannot be extracted profitably given today’s technology (UNEP 2010a). Therefore it seems consistent to combine *resources* and the total anthropogenic stock as both describe deposits for which extraction is currently or potentially feasible and both depend on the technological and economic development in the future.

3.3.2 Characterization model

In their default characterization model Guinée and colleagues (2001) determine characterization factors for depletion of abiotic resources (see also Box 1.4 in Chapter 1).

$$ADP_{i,\text{ultimate reserves}} = \frac{\text{extraction rate i}}{(\text{ultimate reserves i})^2} \times \frac{(\text{ultimate reserves antimony})^2}{\text{extraction rate antimony}} \qquad \text{(Eq. 3)}$$

As shown in equation 3, $ADP_{i,\text{ultimate reserves}}$ is calculated by first dividing the extraction rate of raw material i by the square of the ultimate reserves of raw material i totally available on earth. Second, this ratio is put in relation to the extraction-ultimate-reserve-ratio of the reference resource *antimony*. The contribution to the depletion of abiotic resources of a product is calculated by multiplying each raw material input (m_i) into the product system under study by its corresponding characterization factor, the abiotic depletion potential (ADP_i) (see Eq. 4) (Guinée et al. 2001).

$$ADP = \Sigma\, ADP_i \times m_i \qquad \text{(Eq. 4)}$$

In order to determine the new characterization factors AADP, the characterization models proposed by Guinée et al. (2002) are modified in two steps. First, resources are used instead of ultimate or economic reserves (see Eq. 5).

$$ADP_{i,resources} = \frac{\text{extraction rate i}}{(\text{resources i})^2} \times \frac{(\text{resources antimony})^2}{\text{extraction rate antimony}} \qquad \text{(Eq. 5)}$$

Second, the anthropogenic stock of a raw material (as defined in previous sections) is added to the resource (see Eq. 6).

$$AADP_{i,resources} = \frac{\text{extraction rate i}}{(\text{resources i} + \text{anthropogenic stock i})^2} \times \frac{(\text{resources antimony} + \text{anthropogenic stock antimony})^2}{\text{extraction rate antimony}} \qquad \text{(Eq. 6)}$$

In this study almost all data for extraction rates, resources and stocks were derived from the United States Geological Survey (e.g. (USGS 2010b)). For conventional ADP values according to the CML guideline are applied (Guinée et al. 2002). The impact assessment for the category depletion of abiotic resources was accomplished by applying the conventional ADP, the same model, but replacing ultimate reserves with resources ($ADP_{resources}$) and the anthropogenic stock extended abiotic depletion potential (AADP). The characterization factor $ADP_{resources}$ was added as an intermediate step for identifying the influence anthropogenic stocks have on the results. Based on the characterization models shown in Eq. 5 and Eq. 6, characterization factors for a range of relevant metals are calculated and the newly parameterized model is tested by evaluating a fictional life cycle inventory. For simplicity the fictional inventory contains the elementary input flows of "1 kg" of each material. The extraction rate used as the basis for the conventional ADP model refers to the removal of a certain quantity of a resource from nature (Lindeijer et al. 2002). In the AADP model, only the amount of the resources that are lost (e.g., by means of dissipation) would affect the depletion and would need to be accounted for, requiring adaptions on an inventory level.[22] However, as this needs to be determined on a product basis and in relation to existing inventories, a conservative approach is taken in this dissertation, assuming that all that is extracted is lost.

In the next section the results of the proposed models are presented. Hereby, the results for each "step" of the new parameterization are displayed, enabling an easy comparison and a transparent basis for determining the relevance of anthropogenic stocks.

[22] The decrease of natural stocks (via extraction) equals an increase of the anthropogenic stock. However, dissipative applications and dispersion of materials lead to a greater decrease of natural stocks than an increase in anthropogenic stocks. Thus, overall the available stock is decreasing, but at different rates for individual materials, depending on specific utilization and dissipation rates.

3.4 Results

On the basis of the characterization model described in the previous section, abiotic depletion potentials were calculated. For now, due to limited data access, the focus of this study is on 21 materials only. Table 3.1 shows $ADP_{resources}$ and AADP characterization factors derived from the conventional ADP characterization model (Guinée et al. 2002).

Table 3.1: Characterization factors for material portfolio

Raw material	Extraction rate [t/a][1]	Resource [t][2]	Anthropogenic stock [t][3]	$ADP_{ultimate\ reserves}$ [kg Sb-e./kg][4]	$ADP_{resources}$ [kg Sb-e./kg]	AADP [kg Sb-e./kg]
Al[5]	2,58E+08	7,50E+10	4,75E+09	1,09E-09	6,44E-06	2,34E-05
Be	2,60E+02	8,00E+04	1,33E+04	1,26E-05	5,71E+00	1,72E+01
Cd	2,22E+04	6,00E+06	8,57E+05	1,57E-01	8,66E-02	2,72E-01
Co	1,09E+05	1,50E+07	1,63E+06	1,57E-05	6,80E-02	2,27E-01
Cr	2,33E+07	1,20E+10	1,52E+08	4,43E-04	2,27E-05	9,10E-05
Cu	1,61E+07	3,00E+09	4,47E+08	1,37E-03	2,51E-04	7,82E-04
Fe	2,94E+09	8,00E+11	4,95E+10	5,24E-08	6,45E-07	2,35E-06
Hg	2,01E+03	6,00E+05	4,41E+05	9,22E-02	7,84E-01	1,07E+00
Li	3,41E+04	4,00E+07	6,67E+06	1,15E-05	2,99E-03	9,03E-03
Mn	1,60E+07	1,42E+09	4,37E+08	2,54E-06	1,11E-03	2,67E-03
Mo	2,64E+05	2,00E+07	4,87E+06	1,78E-02	9,27E-02	2,46E-01
Ni	1,94E+06	1,30E+08	4,06E+07	6,53E-05	1,61E-02	3,84E-02
PGM[6]	4,67E+02	1,00E+05	1,10E+04	2,22E+00	6,56E+00	2,18E+01
Pb	4,70E+06	2,00E+09	1,80E+08	6,34E-03	1,65E-04	5,70E-04
Re	5,07E+01	1,10E+04	8,05E+02	6,03E-01	5,88E+01	2,10E+02
S	6,81E+07	5,00E+09	2,32E+09	1,93E-04	3,83E-04	7,33E-04
Sb	1,78E+05	5,00E+06	5,13E+06	1,00E+00	1,00E+00	1,00E+00
Tl	1,00E+01	6,47E+05	3,36E+02	2,43E-05	3,36E-03	1,38E-02
Ti	6,70E+06	2,00E+09	2,39E+08	2,79E-08	2,35E-04	7,71E-04
V	6,24E+04	6,30E+07	1,20E+06	7,70E-07	2,21E-03	8,73E-03
Zn	1,28E+07	1,90E+09	3,45E+08	5,38E-04	4,98E-04	1,47E-03

[1]USGS (2013a) [2]Butterman and Carlin (2004), Deutsches Kupferinstitut (2011), Frondel et al. (2006), Hill and Sehnke (2006), and USGS (2013a) [3]USGS (2013a) [4]according to Guinée (1995), Guinée et al. (2002), and van Oers et al. (2002) [5]Bauxite is used as reference (USGS 2013a) [6]Reference values for platinum are used (van Oers et al. 2002)

The assumption that $ADP_{resources}$ and AADP factors should be larger than ADP factors because material availability decreases when *resources* and anthropogenic stocks are used instead of *ultimate reserves* is not necessarily valid. As all factors express the result in relation to the reference resource *antimony* the characterization factors can hardly be compared directly. Only the ratio of, for example, $ADP_{resources,Cu}$ to $ADP_{resource,Ni}$ can be compared to the ratio of $AADP_{Cu}$ and $AADP_{Ni}$. For the AADP, the difference between the ratios is dependent on the anthropogenic stock-resource-relation of the materials. Hence, materials with relatively large anthropogenic stocks will contribute comparatively less to abiotic depletion than materials with relatively low anthropogenic stocks.

This rather theoretical discussion is illustrated by means of the case study in which a fictional life cycle inventory, consisting of 1 kg of each metal, was evaluated using ADP, $ADP_{resources}$ and AADP. The results on the inventory level and for the impact category depletion of abiotic resources when using ADP, $ADP_{resources}$ or AADP characterization factors are shown in Figure 3.2.

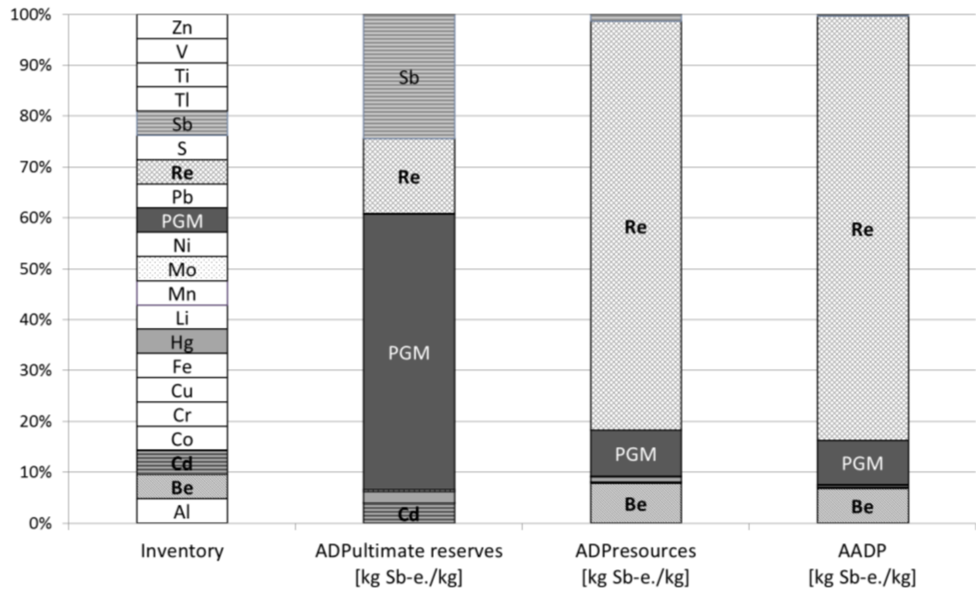

Figure 3.2: Contribution of metals to abiotic resource depletion

In Figure 3.2 only *rhenium* (*Re*), *platinum group metals* (*PGM*), and *antimony* (*Sb*) contribute to the impact assessment results in a noticeable manner while the remaining metals cause minor impacts only. However, while the results of $ADP_{ultimate\ reserves}$ is dominated by the impacts resulting from the abiotic depletion of *antimony*, *rhenium*, *PGM*, and to some extent *cadmium*, $ADP_{resources}$ and AADP are clearly dominated by the depletion of *rhenium*, with slight differences.

In a second analysis shown in Figure 3.3, the dominating metals were excluded from the analysis and the results are again displayed using ADP, $ADP_{resources}$ and AADP characterization models.

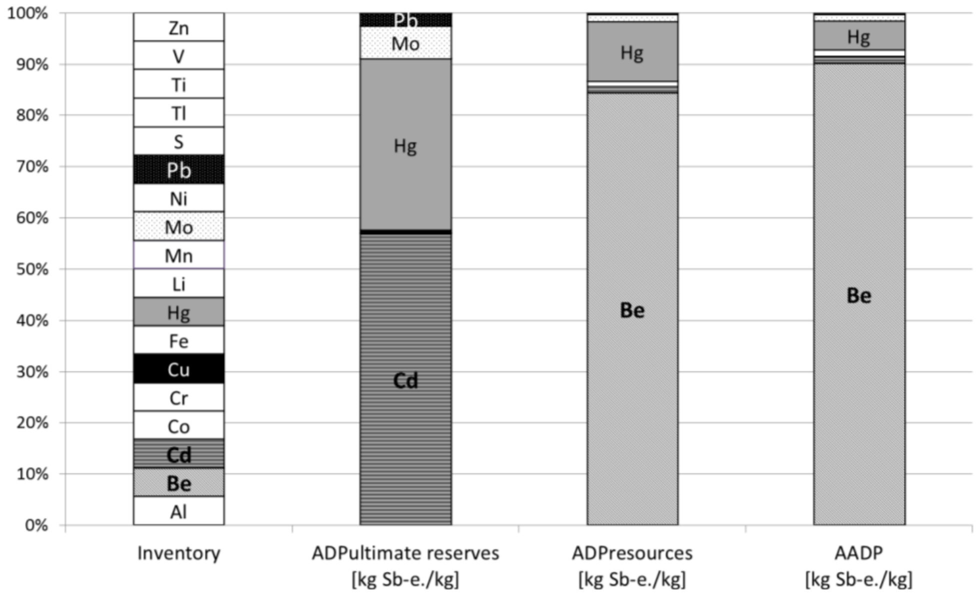

Figure 3.3: Contribution to abiotic resource depletion, excluding *Sb, PGM, Re*

While ADP results in Figure 3.3 are dominated by the abiotic depletion of *cadmium* (*Cd*) and *mercury (Hg), beryllium* (*Be*) contributes most to the $ADP_{resources}$ and AADP category indicator result, again with slight differences. Hence, *cadmium* is regarded as the scarcest metal in the inventory when computing characterization factors based on the ratio of extraction-rate to ultimate reserves. In contrast, when calculating extraction-reserve-ratios by means of the sum of *resources* or *resources* and anthropogenic stocks, *cadmium* is of less importance and *beryllium* is regarded as the most critical metal. Obviously, criticality of certain materials is different based on the new characterization factors, providing different implications for decisions.

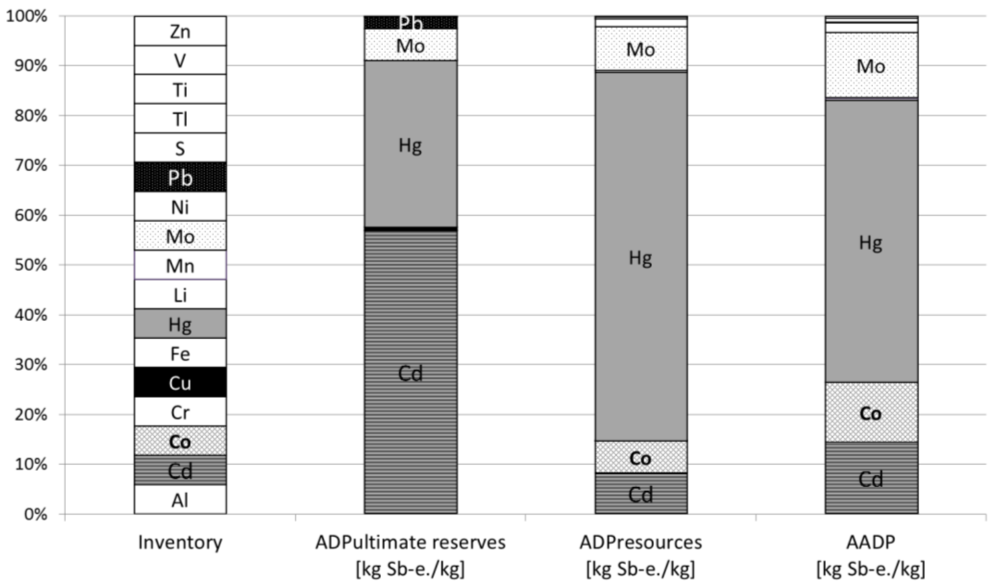

Figure 3.4: Contribution to abiotic resource depletion, excluding *Be*

In Figure 3.4, after excluding beryllium from the examination, a visible difference between $ADP_{resources}$ and AADP can be found. For mercury for example, the stock is almost as large as the resources. Thus, the pressure displayed by the $ADP_{resources}$ should be higher than compared to the pressure displayed by AADP. By means of Figure 3.4 this can be verified. Large stocks are thus reducing the pressure on a resource and lead to a comparably lower impact on the depletion of abiotic resources. However, the overall difference between $ADP_{resources}$ and AADP characterization factors displayed in Figure 3.4 seems to be small. Therefore, in Figure 3.5 the difference of the characterization models is displayed more closely to emphasize the significance of the new approach. Hereby all factors are normalized to *copper (Cu)* for an easier interpretation of results. For materials with large anthropogenic stocks, the characterization factor is decreasing because the denominator is increasing. By assessing the relative change compared to *copper*, for example, $AADP_{Ni}$ to $AADP_{Cu}$, the large Ni-stock will lead to a smaller ratio than the same comparison for $ADP_{resources}$. This confirms that the consideration of anthropogenic stocks lead to different impacts for materials within the characterization models (here: materials with larger anthropogenic stocks than *copper (mercury, antimony, nickel, molybdenum, etc.* contribute comparably less to abiotic depletion). Positive bars in Figure 3.5 represent values beneath 100% for AADP/$ADP_{resources}$, standing for a comparably lower depletion potential compared to *copper* when applying AADP, and vice versa. It is revealed that the impact of anthropogenic stock results in relative differences between -30% and +68% indicating that anthropogenic stocks are significant. Given that in Figure 3.4 the contribution is displayed as a function of the sum of all characterization factors these differences are not as obvious.

Anthropogenic stocks are expected to gain in relevance for future material provision as extractions from nature has grown exponentially in the last two decades, and no slowing down is expected. With growing anthropogenic stocks and increasing data availability the AADP characterization factors will become more important for a realistic assessment of resource depletion.

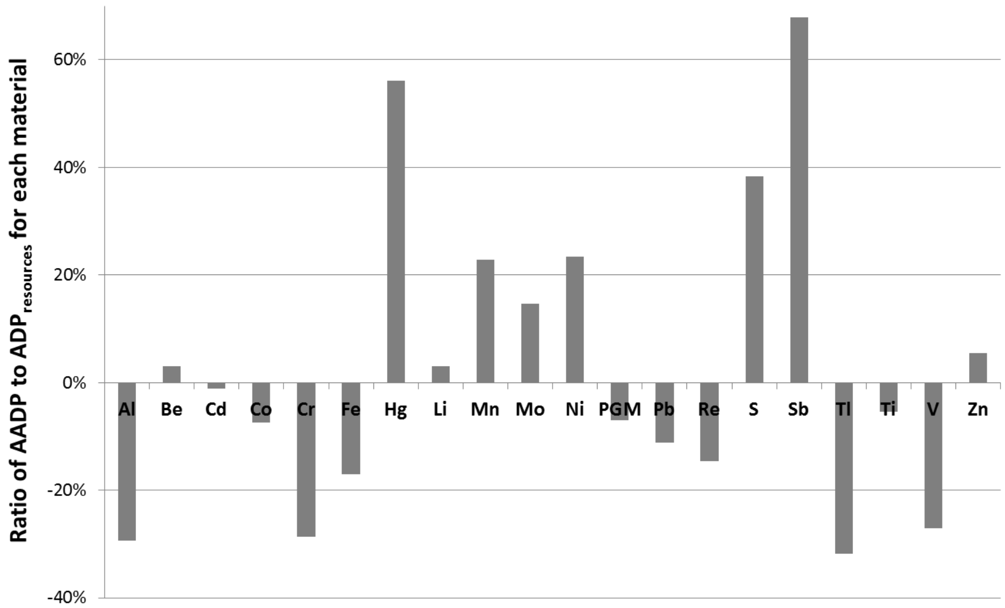

Figure 3.5: Characterization factors $ADP_{resources}$ compared to AADP (normalized to *copper*)

As stated within the definition of the conventional ADP characterization factor (Guinée 1995), reserves of a material are taken into account more than once (by putting a square to the denominator to provide a realistic depiction of resource criticality (when assessing the effect of 1 kg of extraction) (see also Chapter 1). Underlying is the fact that small stocks are a more important indicator for resources depletion than large extraction rates. Simply comparing extraction rates and stocks would lead to different results. This implies that the stocks of materials have a comparably higher importance than extraction rates within the calculation of characterization factors (Guinée 1995). Thus, the difference between the extraction rates used for conventional ADP and for $ADP_{resources}$/AADP (USGS 2014a) should not lead to significantly different results.

In Figure 3.6 the results of the AADP assessment are compared to the results of the conventional $ADP_{ultimate\ reserves}$ model.[23] The results of the AADP and ADP methods differ significantly. Materials that have a high concentration in the earth's crust are not necessarily deemed more available for human use as mineable concentrations and extractability is limited.

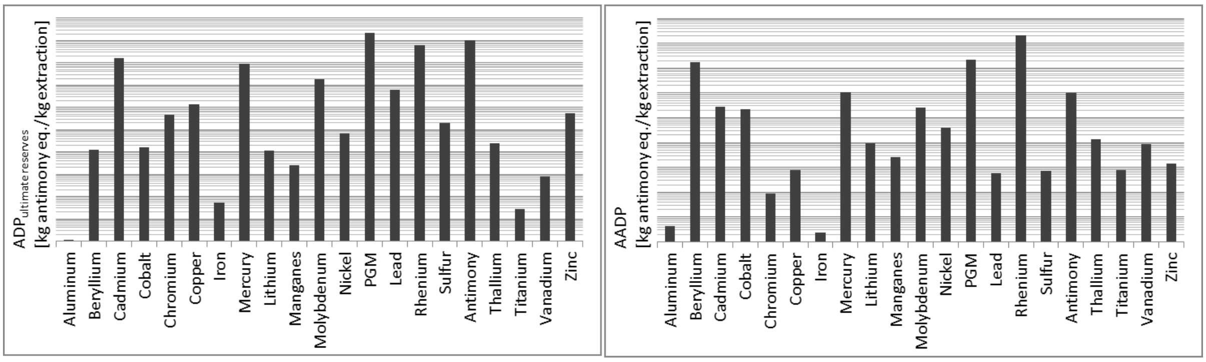

Figure 3.6: Physical availability of metals – $ADP_{ultimate\ reserves}$ and AADP (ADP data based on van Oers et al. 2002). ADP and AADP results are adapted to fit a logarithmic scale.

The results confirm, that materials with high anthropogenic stocks are comparatively less critical (when compared to conventional ADP results) than materials with a low anthropogenic stock. It seems that the AADP characterization model can enable a more realistic assessment of depletion of abiotic resources, for example with regard the implementation of new technologies. By accounting for the loss of resource AADP results provide insight into materials that are used in an "unsustainable" way. However, a complementary use of the conventional ADP and AADP makes sense, when not only the availability of the functionality of resources needs to be assessed, but also the availability of resources in the natural environment. Natural depletion of abiotic resource occurs only by means of geologic extraction. However, there are still challenges which currently remain unsolved. In the following section these shortcomings and additional considerations regarding the application of the model are addressed.

[23]No numbers for the y-axis are included in the figure, as the ADP and the AADP are relative measures. Absolute values cannot be compared between the different methods and are thus not displayed to avoid misinterpretation of results.

3.5 Additional considerations

In this section some additional consideration to the new parameterization for the assessment of abiotic resource depletion are discussed.

The difficulty of defining ultimately extractable amounts of resources and lack of data currently inhibits the calculation of a larger set of characterization factors. Results of the assessment are highly dependent on the definition of resource numbers. Thus, a closer examination of published numbers and the relevance of these numbers for determining the ultimately extractable geologic resources need to be assessed. *Resource* numbers used as a basis for the new parameterization are known, estimated or interpreted from specific geological evidence and can change with increasing geological knowledge (Crowson 2011; Henley and Allington 2013). Thus, a more precise evaluation of the extractable global resource is needed as a next step. Initial discussion on this topic is provided in Appendix II. Furthermore, the definition of the amount of anthropogenic stock ultimately available for (future) use needs to be assessed in more detail. Dissipation of resources in the anthropogenic stock is not considered to the necessary extent in this dissertation. In further works, as a starting point a differentiation between base and noble metals and the potential effects of corrosion could be made. However, as already mentioned in previous sections, dissipative application of materials differs to a great extent and individual data would be necessary for depicting a realistic picture of the potentially available anthropogenic stocks. Data regarding dissipation of individual materials is hard to obtain, as dissipation strongly depends on product specific characteristics. Thus, the challenge of a realistic representation of anthropogenic stocks remains and current data provides only a rough estimate. For future advancements of the methods, detailed analysis of material flows or technological applications is needed to define anthropogenic stocks. Furthermore, from a methodological point of view it is still unclear how anthropogenic stocks can be calculated for fossil fuels, for which plastics available in the technosphere might serve as anthropogenic deposit to a certain degree.

In this dissertation, depletion is assessed as a long term problems and the developed models aim at assessing availability of resource for future generations. For the assessment of physical resource availability from a shorter term perspective, only materials that are currently or potentially extractable would be considered (e.g., *economic reserves*). This would lead to several challenges of defining the available anthropogenic stock as a close examination of the in-use, hibernating and deposited stock and a differentiation between applications would need to be made (e.g., materials in products with long life spans could not be considered as part of the anthropogenic stock).

The implementation of the AADP needs to be realigned when acknowledging the functional value of resources. As highlighted in the previous sections, not the use as such, but the loss of a material is of concern. Thus, depletion of resources should not be focused on the extraction of resources, but on the dissipative use. Unfavorable combinations of materials in products, however, will increase losses in the end-of-life phase and recycling (Hagelüken and Meskers 2010; Reuter et al. 2005). This would need to be taken in account, rather than the amount used as such. In reality, application of this model would need to focus on the “destiny” of the material, rather than its source and according adaptations with regard to the used inventory data would need to be made. The application of materials in a manner that allows for reuse and recycling is not of concern and would thus not be associated with any depletion potential. In this case the overall resource stock stays the same, and no depletion occurs. The extraction of resource from nature decreases the geologic resource stock but increases the anthropogenic stock. The overall resource stock would only be diminished by dissipation and inevitable loss of resources. This relation of natural and anthropogenic stocks in the context of the overall resource stock potentially available for human use is displayed in Figure 3.7.

Whether the resources are extracted from the geologic or the anthropogenic stock is of no concern for society with regard to the provision of the desired function. The AADP emphasizes the fact that resources with high anthropogenic stocks that remain in a potentially useable form in the environment can be evaluated as less critical as resource that have low anthropogenic stocks and are mainly used dissipative. Product designers need to enable recycling and preserve the function of resources by evaluating metal combinations and assembly and avoid the use of certain elements in highly dispersed states that cannot be recovered (Graedel et al. 2014).

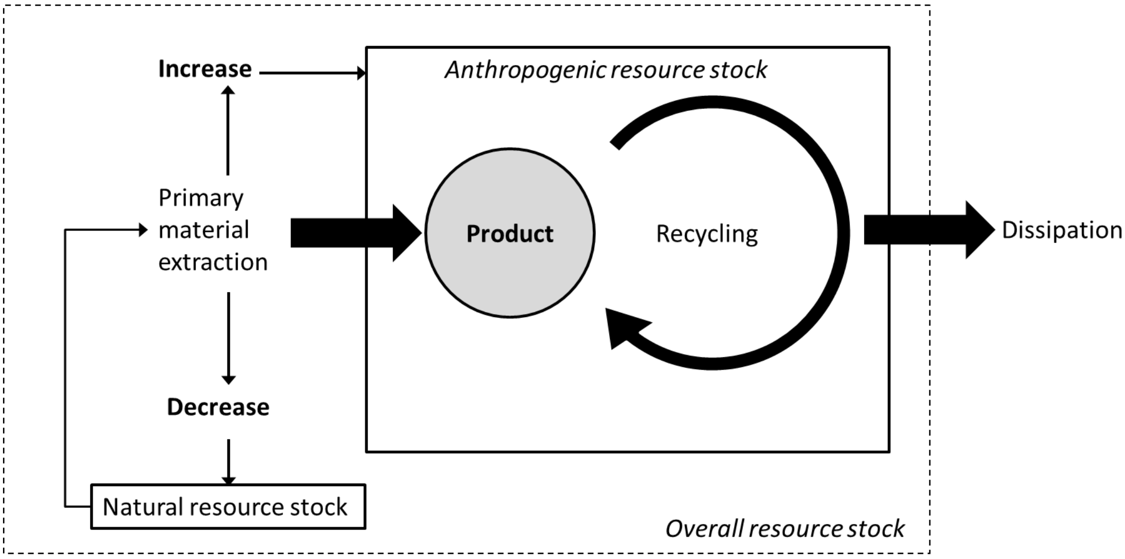

Figure 3.7: The anthropogenic stock extended depletion mechanism

4 ECONOMIC CONSTRAINTS TO RESOURCE SUPPLY – THE ECONOMIC RESOURCE SCARCITY POTENTIAL

Abstract

Resource availability can be effectively constrained by economic factors, beyond a physical of geological dimension. Mineral resources are not distributed evenly around the globe. This creates challenges with regard to the access of certain materials. Aim of this chapter is the development of a new model for the assessment of resource provision capability from an economic angle, complementing existing models towards a comprehensive assessment of resource availability. The assessment of market induced constraints enables an identification of supply risks associated with resource use. In step with actual practice such an assessment provides added value compared to conventional resource assessment within LCA. Analysis of resource availability including economic information is of major importance to sustain industrial production.

A new model is developed in this chapter for the assessment of economic resource availability based on existing LCA methodology and terminology. A single score result can be calculated providing information about the economic resource scarcity potential (ESP) of different resources. The model allows for a more realistic assessment of resource availability beyond geologic finiteness. The supply risk associated with resource use can be assessed and bottlenecks within the supply chain can be identified. Rare earths for example show a high supply risk in several categories resulting in potential constraints in resource supply.

The assessment delivers a basis for developing appropriate mitigation measures and to increase resilience towards supply disruptions. By including an economic dimension into resource availability assessment a contribution towards LCSA is achieved.

This chapter is based on a publication in the International Journal of Life Cycle Assessment but contains additional background information and discussion on this topic.

Published as: Schneider L, Berger M, Schüler-Hainsch E, Knöfel S, Ruhland K, Mosig J, Bach V, Finkbeiner M (2013) The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment. International Journal of Life Cycle Assessment 19 (3): 601-610

4.1 Economic constraints to resource supply

There are several types of interventions on free markets, privileging for example national interests and potentially affecting the supply of materials for certain interest groups. In this context, the assessment of risks along the supply chain of different materials is essential for determining potential constraints in the provision of certain materials relevant for products and production processes. For assessing potential interruptions in the supply chain, a comprehensive set of indicators needs to be assessed. This section will provide an overview of potential market induced constraints to resource supply. In a later step, these indicators will be integrated into a holistic model that assesses resource availability for products and production processes.

Many resources used in industrial processes come from faraway areas like Africa or China. In countries like Africa, society cannot themselves afford to use much of what is produced (Zwartendyk et al. 1987), thus, rendering the material available for use in industrialized countries. However, as the example of China shows, this situation might change significantly in the future.[24]

The effects of market risks associated with different materials are difficult to analyze as supply chains are very complex and globalized. An appropriate set of indicators is needed to uncover potential risks and to identify bottlenecks associated with resource supply. In Table 4.1 an overview of several criteria potentially affecting resource availability and supply is provided. Economic constraints can occur by a host of things, resulting in potential interruptions in the supply chain of materials. By analyzing economic criteria supply risks can be identified and more informed decisions regarding choice and use of resources for products can be made.

Table 4.1: Exemplary overview of economic criteria potentially affecting resource supply

- Availability of reserves	- Co-production/companion metal fraction
- Economic stability	- Potential for substitution
- Concentration of reserves or production to certain countries	- Competing technologies
- Concentration of production activities to certain companies	- Demand growth/change rate of demand
- Trade barriers	- Logistic constraints
- Volatility	- Availability of anthropogenic stocks
- Price elasticity of demand and supply	- Capacity utilization
- Recycling/availability of secondary material	- Availability of energy carriers
- Societal acceptance of mining activities	- Dissipative use of resources
- Susceptibility to natural disasters	- Investment in mining
- Transportation costs	- Production costs

In this dissertation, a new model is developed for modelling economic resource provision capability for application in product assessment. For the determination of potential economic constraints, the political and institutional background of resource extraction and availability is relevant, and geopolitical, political and regulatory constraints need to be assessed.

No single measure is appropriate for the assessment of risk for all time scales or all interested parties. Supply risk is composed of multiple aspects. In this context, following aspects are assessed that pose a potential risk to resource provision capability of certain materials:

- Geopolitical: Geographical location of reserves and production process is an important factor for the availability of materials
- Political: Risks related to governance processes and political situations in relevant countries in the supply chain of materials

[24] To protect national interests, the Chinese government imposes for example trade barriers for *rare earths*.

- Socio-economic: Human development is an important factor for social and economic stability that are the basis for functioning markets.
- Demand growth: Demand growth can be used to indicate potential pressure on timely supply.
- Technical: characteristic of mining processes that pose a potential risk to timely resource supply (co-production) and availability of recycled material as an aspect for risk reduction

Economic constraints directly affect the supply of materials for products and production processes. While the physical depletion of resources is a continuous process caused by the use and extraction of materials, the scarcity induced by economic constraints can change over time and can decrease or increase. From a company or enterprise perspective, shortages of a material or disruptions in a supply chain can have serious consequences.

Focus of the evaluation in this chapter is on metals. In Table 4.2 an overview of the material portfolio addressed in this section is provided. Several metals are assessed, including base metals (e.g., *iron* and *copper*), special metals (e.g., *cobalt* or *lithium*) and precious metals (e.g., *gold* and *silver*).

Table 4.2: Material portfolio

Aluminum[1]	Lead	Rare earths
Chromium	Lithium	Silver
Cobalt	Magnesium	Tin
Copper	Molybdenum	Titanium
Gold	Nickel	Zinc
Iron	Platinum group metals (PGM)	

[1]based on data for bauxite (USGS 2014a)

In the following sections, choice of criteria and indicators is elaborated and a detailed description of all indicators included in the assessment of the economic dimension of supply risk within this dissertation is given. In Chapter 4.3 the methodology of the proposed model for the assessment of resource availability from an economic angle is described in more detail

4.2 Criteria and indicators

This section provides an overview of criteria and indicators used to assess potential resource scarcity induced by economic constraints. The selection of criteria and the definition of indicators are described in detail in this section as no methodological basis is available (contrary to the assessment of environmental or social aspects that rely on existing methods and databases).

The criteria and indicator selection in this work takes up and complements existing works (see, i.a., Buchert et al. 2009; Erdmann and Behrendt 2010; Erdmann and Graedel 2011; European Commission 2010a; Graedel et al. 2012a; National Research Council 2008; Rosenau-Tornow et al. 2009; Yellishetty et al. 2011). Regarding the selection of criteria and indicators for quantification, data availability proves to be the main limiting factor. Even though, choice of criteria and indicators should be as broad as possible, several criteria have to be neglected at present as data availability and quality is poor. Chosen indicators are based on publicly available and accepted databases or publications. In the following sections, criteria and indicators as used in this work are introduced in more detail, including argumentation for their relevance in the context of the assessment of economic constraints to resource availability.

Following criteria are specified in the next sections:

- Availability of reserves
- Concentration of production and reserves
- Companion metals
- Use of recycled material
- Governance stability
- Socio-economic stability
- Trade barriers
- Demand growth

All described criteria might constrain the supply security of resources and consequently cause supply shortages. These criteria are related to the country of production, and aim at assessing the risk that originates in the dependence on imports from these countries, or refer to trends or circumstances that might results in interruptions of supply. In Figure 4.1 the different criteria are classified in the context of the analyzed system (resource provision level). Some of these aspects are frequently addressed in the context of resource scarcity assessments but no holistic approach, considering so many different constraints is available so far.

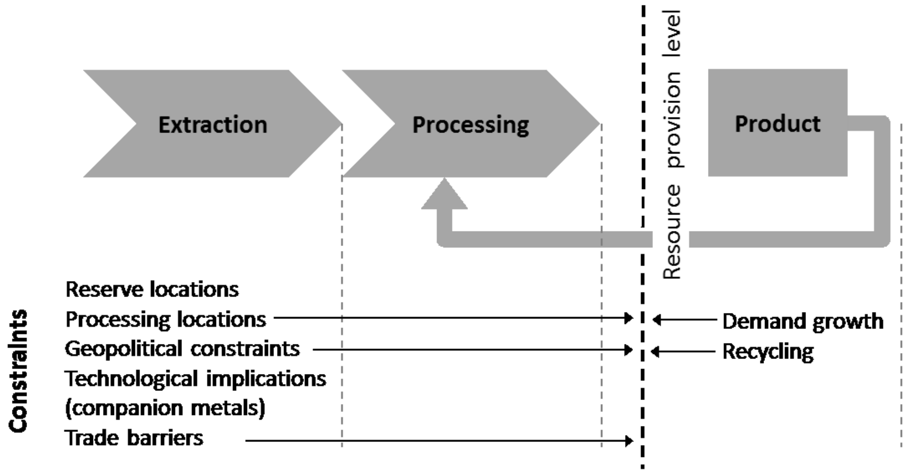

Figure 4.1: Economic constraints in the supply chain (adapted from DOE 2010)

In the following sections an overview of criteria and indicators addressed in this work is provided. The indicator values for the different materials can be found in Appendix III. To what extend these individual aspects affect availability of resources and pose a threat to continued supply is assessed within later sections of this chapter.

4.2.1 Availability of reserves

Per definition of the USGS *reserves* are "that part of a resource which could be economically extracted or produced at the time of determination" (USGS 2013) displaying current production technologies. Reserve figures do not reflect the total amount of mineral potentially available and thus are not a reliable indicator for displaying the absolute availability of a resource or for impending exhaustion (see also discussion in Chapter 1). Instead, the assessment of the availability of *reserves* has a strong economic dimension. *Reserves* are those resource concentrations which companies have proven they can extract with profit, given legal requirements, extractive and processing technologies and prices of a certain moment (Buijs and Sievers 2012). If prices for a metal rise, the amount of available reserves also increases as lower grade ores that before have been classifies as non-economic can then be mined (Sievers 2012).

Availability of resources can be assessed by means of the *reserve-to-production ratio* (also referred to as *depletion time*) that depicts the amount of time it would take to deplete *economic reserves* at the current rate of extraction. The *reserve-to-production ratio* represents a snapshot in a dynamic system (Graedel et al. 2012b; Sievers 2012) and the indicator has been criticized for failing to take into account the dynamic nature of reserves. Even though the *reserve-to-production* ratio changes over time, it is a useful indicator to evaluate periodic availability of a resource (Graedel et al. 2012b). Reserves can serve as a measure of exploitation planning and deposit type (Zwartendyk et al. 1987).

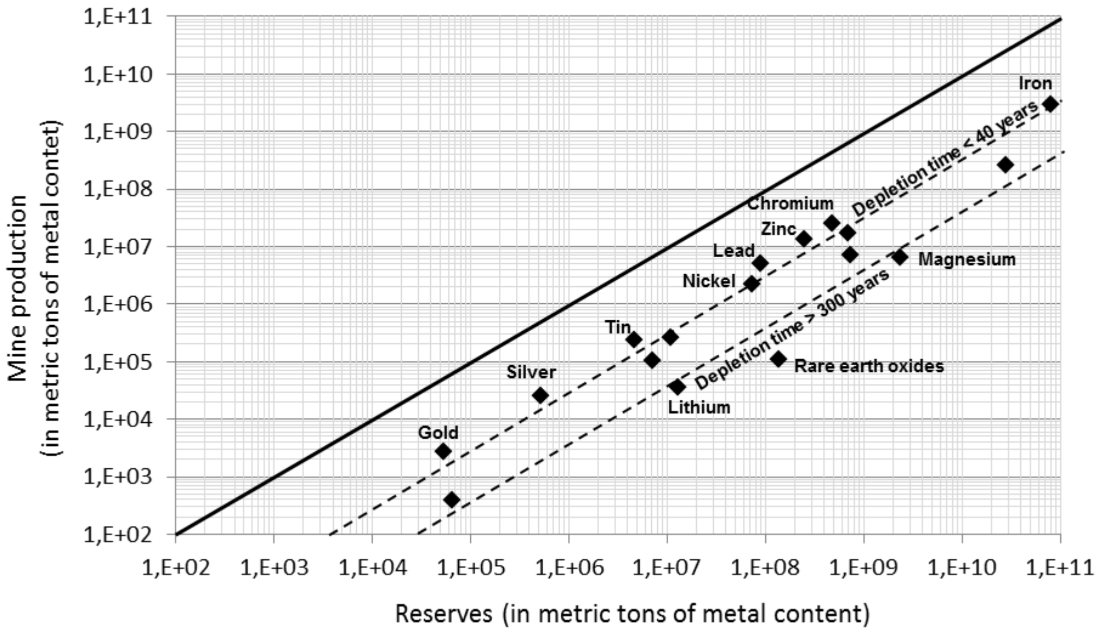

Figure 4.2: Reserves and production rates (based on data published by the U.S. Geological Survey, USGS 2013a)

The depletion time for the materials in the assessed portfolio varies significantly. In Figure 4.2 the reserves are plotted against the production rates, indicating the lifetime of the reserves (depletion time). In the Figure, metals having a depletion time of less than 40 years and metals having a depletion time of over 300 years are highlighted. The figure shows that materials which are commonly perceived as scarce (e.g. *rare earths* or *PGM*) have actually very long depletion times, while materials such as *zinc* or *chromium* have *reserve-to-production ratios* below 20 years.[25]

In Figure 4.3 a detailed overview of reserve data and the *reserve-to-production ratio* for *copper* is given. The historical developments of reserve-to production ratios of many minerals show that there is no threatening decline. Still, as proposed by Wellmer and Becker-Platen (2002), the indicator can be used to signify the available time-buffer during which functionally equivalent substitutes must be found. The ratio can give an idea as to which mineral raw materials should be considered in view of a preventive resource management (Wolfensberger et al. 2007).

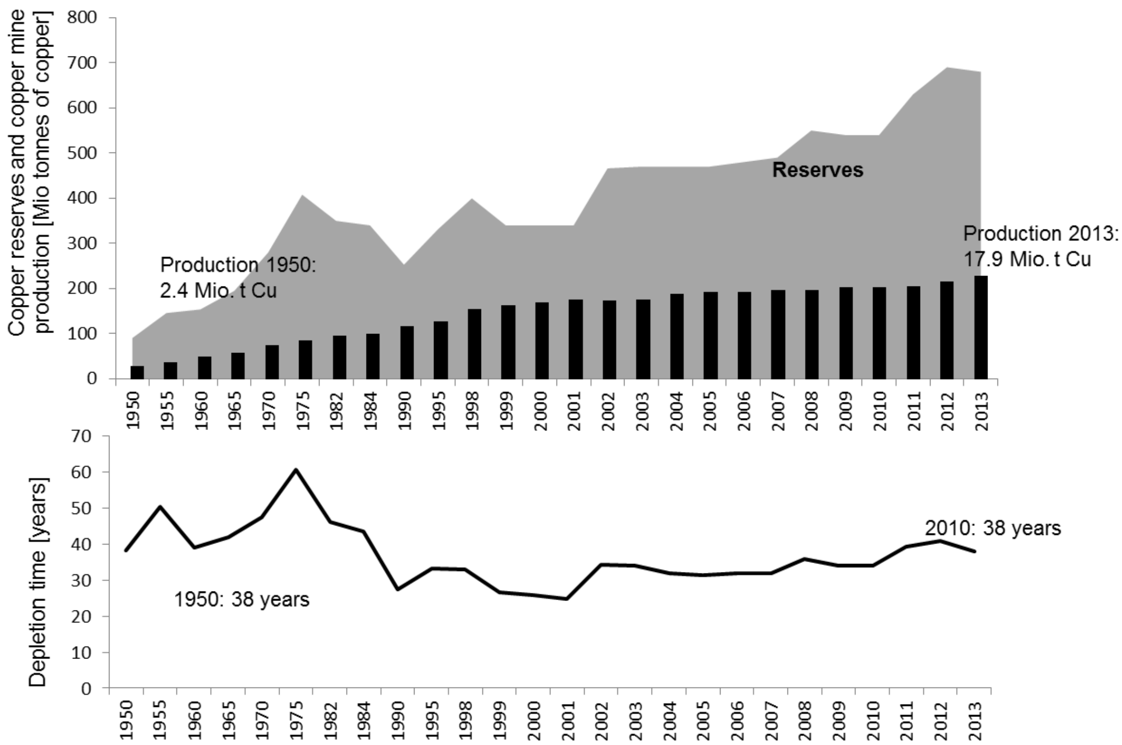

Figure 4.3: Reserves and depletion time of *copper* (source: Notman 1935; U.S. Bureau of Mines 1960, 1975; USGS 2014a)

4.2.2 Concentration of production and reserves

Abiotic resources are geographically unevenly distributed over the globe (Crowson 2011; Kesler 1994; Misra 2000; Weterings et al. 2013). Mineral deposits have a place value and are concentrated in specific parts of the earth's crust. The location of the resources does have huge implications for resource security as most countries are highly dependent on resource imports.[26] The uneven geographical distribution as such increases the risk for supply

[25] An overview of the economic reserves and mine production of all assessed metals is provided in Appendix III.

[26] The European Union for example depends on the import of metal ores. 100% of *PGM ores*, *rare earth ores*, *cobalt*, or *molybdenum* are imported. Only very small shares of metals are produced inside of the EU (Brown et al. 2014).

disruptions. A high concentration of one activity (e.g., mining) in few countries is always associated with a high risk regarding the accessibility of a resource. Furthermore, the corporate concentration of mine production can be high when only few companies control the global market and production is concentrated in oligopolies (e.g., for *PGM*) (European Commission 2010a). Thus, even if mines are distributed over several countries, if only one mining company owns all facilities higher risks occur.

An assessment of the distribution of reserves or production activities indicates the sensitivity of the metal supply to disruptions. The assessment of country or company concentration is relevant at all stages of the supply chain. A common measure of market concentration is the Herfindahl- Hirschman Index (HHI). The indicator is calculated by squaring the market share of each company or country with regard to the production/reserves and the summation of the results (von der Lippe 1993).[27] The variability of the HHI is much smaller for large resource markets (e.g., base metals) than for small markets, as the impact of one new production facility upon the overall market is much smaller (Buijs and Sievers 2012). In small markets even the discovery of a single new deposit may have a major impact on global reserves and production of some resources (European Commission 2010a). For resource markets with small volumes and little overall production, dominance of few producers is much more likely.

In Figure 4.4 the reserves and production of PGM is displayed, highlighting the concentration in only a few countries in the world (in total 40 production sites are covered) (IntierraRMG 2013). Contrary, in Figure 4.5 reserves and production of *copper* are displayed (covering 278 production sites), showing a much greater distribution of production sites in different countries and less concentration and consequently lower risks for supply disruption.

Figure 4.4: World mine production PGM in 2012, circles indicating production sites (source: IntierraRMG 2013)

[27]Companies in China are controlled by the state and are thus treated as “one company” in the later evaluation.

Figure 4.5: World mine production *copper* in 2012, circles indicating production sites (source: IntierraRMG 2013)

4.2.3 Companion metals

Mineral deposits often contain a variety of different products. Metals frequently occur in the ores of metals with similar physical and chemical properties. Such metals are not the direct target of mining but rather are “companions” (trace constitutes) in the ores of the more common metals (their “hosts”) (Achzet et al. 2011; Graedel et al. 2012b; Graedel and Erdmann 2012).

The extraction of companion metals is directly dependent on the extraction rate of the carrier metals (Crowson 2011). Consequently, the actual scarcity of companion elements may differ from the physical scarcity (geologic availability), due to the specific extraction rate of the carrier metal. Often a differentiation between by-products and coupled elements is made. By-products are substances of value produced as a results of manufacturing another, usually more valuable, substance (Rankin 2011). Coupled elements are elements that are found in the same group, but without a carrier metals (e.g., *PGM, rare earths*). They also have to be mined and processed together (European Commission 2010a). As usually one element in the group becomes the driver for production, this work evaluates by-product metals and coupled elements without further differentiation.

The economic drivers for mining is clearly the host metal (Hagelüken and Meskers 2010). Thus, supply of companion metals is associated with potentially higher risks as the volume mined cannot be easily adapted to a change in market demand. Metals that are produced as by-products cannot always respond quickly enough to meet demand requirements and significant time delays can result (Hagelüken and Meskers 2010). The interconnectivity of resources plays an important role in the determination of supply risk associated with individual resources due to complex pricing and technical limits to adapt production (Hagelüken and Meskers 2010; Reuter et al. 2005). Carrier metals are in general considered to be less vulnerable to supply risk than companion metals. Thus, as an indicator the percentage of a metal mined as companion metal is used to assess potential supply risk. The companion metal fraction describes the supply risk associated with resources that depend on the magnitude of mining of carrier or "host" metals (Graedel et al. 2012a; Graedel and Erdmann 2012). Some elements are by-product elements but also mined on their own (e.g. *cobalt*, *molybdenum*, *gold*, *silver*, *PGM*) (Hagelüken and Meskers 2010).

4.2.4 Use of recycled material

The recyclability of an element needs to be taken into account when determining the availability of resources (Graedel and Klee 2002). Recycling can be an efficient mechanism to secure supply (UNEP 2011). From a product perspective, primary metal consumption can be reduced by the use of secondary material, thus relieving pressure on virgin resource supplies (Graedel and Erdmann 2012). Use of recycled material can be seen as a risk-reducing filter, as it decreases the amount of virgin material needed as input for product system. There are various concepts for measuring recycling (UNEP 2011c). The recycling input rate (recycled content) indicates which percentage of metal input originates from recycled material. The recycled content is defined as the annual tonnage of material scrap consumed divided by the tonnage of material produced and depends on the amount of scrap available (European Commission 2010a; UNEP 2011). Thus, even with a high recycling rate, the recycled content can be low. The consideration of the recycled content in the context of determining economic constraints makes sense, as the amount of secondary material decreases the primary supply risk. Furthermore, the recycling is an important measure in the context of sustainable development (see also discussion provided in Chapter 3).

The reverse of the recycled content, the new material content, indicates how much primary material is used in the production of a specific material on an average basis. As primary supply (as evaluated in this study) is subject to restrictions, the new material content provides a relevant reference for the determination of supply risk. However, it needs to be acknowledged, that secondary material as such underlies supply risks, too, determined by the site of the recycling facilities etc. This will be addressed again in later sections of this chapter.

4.2.5 Governance stability

Risks related to policies and regulations can have an effect on resource availability. The absence of a fair and reasonable legal system or high levels of corruption can lead to interruptions in the supply of certain materials. Even though focus of this indicator is on overall investment and not on supply security of resources in specific (Rosenau-Tornow et al. 2009), the Worldwide Governance Indicators (WGI) are used as an approximation to model stability of governance processes of different countries (The World Bank Group 2012). In Figure 4.6 the correlation between the individual dimensions is highlighted. Results are considered as similar and correlations as strong or significant, if the coefficient of determination is greater than 0.65 (Berger and Finkbeiner 2011). Consequently, of indicators with high correlation only one was chosen. In the context of assessing governance stability in this dissertation, an aggregated indicator is used, based on three of the WGI dimensions that show only very low correlation: *voice and accountability*, *political stability and absence of violence* and *government effectiveness*.

	Voice & Accountability	Political stability & absence of violence	Government effectiveness	Regulatory quality	Rule of law	Control of corruption
Voice & accountability		0,50	0,58	0,65	0,68	0,60
Political stability & absence of violence			0,47	0,36	0,62	0,59
Government effectiveness					0,87	0,86
Regulatory quality					0,79	0,72
Rule of law						0,89
Control of corruption						

Figure 4.6: Correlation of WGI dimensions (based on data published by The World Bank Group 2012)

4.2.6 Socio-economic stability

Economic stability also depends on human development. Social progress is a relevant indicator for the stability of a country. To determine the access to resources, the stability of a country also needs to be assessed based on socio-economic aspects. The inclusion of socio-economic indicators is intended to provide a basis for evaluating the level of social progress of a country under the philosophy that a high level of social progress and human development will correlate with stable markets and lower chances for conflicts, etc.

As defined in this work, the socio-economic stability refers to social and economic circumstances in the context of their impact on resource provision capability. By means of the socio-economic stability, policies and circumstances that enable trade and allow for resource provision can be considered. Thus, the Human Development Index (HDI) is evaluated and included in the assessment for describing socio-economic stability of different countries (Graedel et al. 2012a; UNDP 2011). The HDI is computed as the arithmetic average of income, education, and health indices (Binder et al. 2006; UNDP 2011). The corresponding indicator represents a statistic for life expectancy, education and income referring to social and economic development. The index is used to indicate and measure the development of countries. The HDI associated with the different materials is calculated by weighting the country-specific HDI with the respective production of the material in the different countries.

4.2.7 Trade barriers

Trade barriers are government-induced restrictions on international trade by means of export quotas, taxes, tariffs etc. leading to increasing prices or physical shortages of resources. These measures can have negative effects on the continued supply of resources and the associated risk needs to be assessed. Trade barriers may distort international trade and access to materials by reducing export and import opportunities (World Economic Forum 2012). In the context of evaluating resource provision capability all measures that constraint availability of resources or constraint "exchange" of resources need to be assessed. Thus, no differentiation between tariff and non-tariff measures is made. Trade barriers can occur at any stage of the supply chain.[28] For addressing trade barriers, appropriate indicators need to be used. In this section, two indicators are described: the Enabling Trade Index (ETI) and data on trade barriers published by the BDI (Bundesverband der Deutschen Industrie e.V.). Other indicators are available, but do not fit the context of this work.[29]

The ETI measures factors that facility the trade in goods across borders and evaluates whether economies have in place necessary attributes for enabling trade (e.g. policies and services that facilitate the trade in goods across borders) (World Economic Forum 2012). Within the index, not only policies regarding border obstacles, such as tariffs and non-tariff barriers are assessed but also policies that facilitate trade with e.g. better infrastructure and telecommunication or measures that reduce transaction costs (e.g. improved regulatory and security regimes) (World Economic Forum 2012). The ETI addresses many aspects that go beyond the existence of trade barriers, but also address other issues referring to factors that facilitate trade in general. Those are often closely linked with the general economic development of countries, also resulting in the fact, that developed countries generally rank higher in enabling trade than emerging ones (World Economic Forum 2012). Thus, the indicator as such could be rather used to assess economic development in general, but is not explicitly assessing the existence of trade barriers. Even though the aggregated indicator does not seem appropriate to measuring trade and trade barriers, one of the "pillars" describing the domestic and foreign *market access* (measuring "the extent to which the policy framework of the country welcomes foreign goods into the economy and enables access to foreign markets for its exporters"(World Economic Forum 2012)) could be used. However, as this indicator provides no conclusion with regard to the trade barriers associated with specific metals and minerals, it is not further evaluated in the main part of this work. Instead, the data on trade barriers as published by the BDI is used as a basis addressing the distortion of trade and competition in different countries and for specific materials (BDI 2010). The respective indicator represents the percentage of production of a certain resource underlying barriers. Any potential barrier to trade will be considered (including tariff and non-tariff measures) (BDI 2010). Based on these data, the amount of material underlying trade barriers can be determined.

4.2.8 Demand growth

Demand growth can be used to indicate potential pressure on timely supply. Different technologies may compete for a single resource. Hence, an increased demand in a product system can lower the availability in another application drastically (Wäger and Classen 2006). In this dissertation, annual growth rates for the resources are considered. Underlying assumption of this work is that past trends are assumed to continue and demand growth is

[28]In the context of this work, only the export risks of the producing countries are determined.

[29]Services Trade Restriction for example analyze trade policies affecting trade in services (Borchert et al. 2012b). However, the current database focuses only on five major services sectors, financial services, telecommunications, retail distribution, transportation and professional services (Borchert et al. 2012a), and thus does not provide relevant information with regard to trade restrictions of resources like metals.

assessed based on past demand growth (average annual growth rate for the past 20 years). However, one powerful force influencing the demand for resources are technological changes (see, e.g., European Commission 2010a). If available, future demand considerations are included in the calculation for those materials that are essential for emerging technologies and are assumed to experience significant increase in demand over the next years (Angerer et al. 2009a; USGS 2013).

To determine precise demand growth data of individual metals can be difficult. Thus, if no other data is available, the annual growth of mine production is used based on the compound annual growth rate. In general, it can be expected that the demand growth is slightly higher than the mine production. This is especially true for metals with already high recycling rates. However, this difference is only marginal. In Figure 4.7 an overview of this relation is provided. While the growth rate of *copper* production increased by averagely 3.0% in the past 50 years, demand growth (determined by means of end-use data) increased by 3.1%.

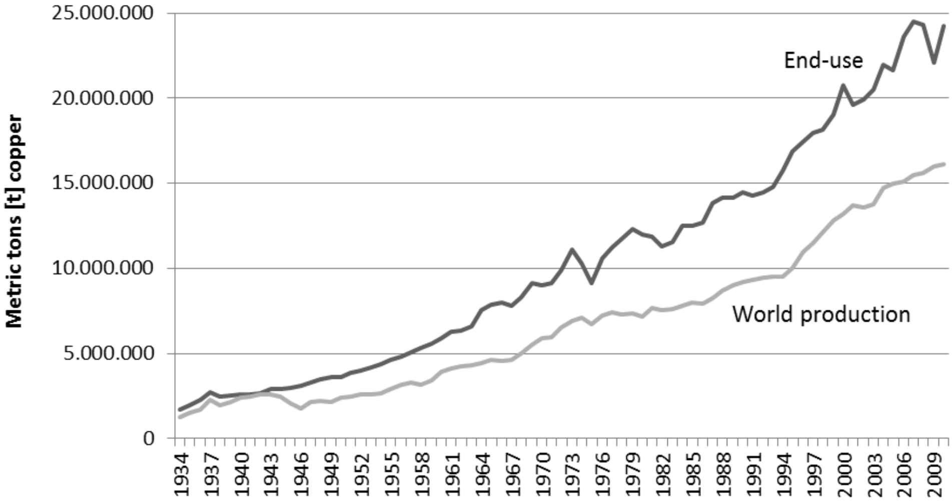

Figure 4.7: Growth rates *copper* – World production and end-use (Ayres et al. 2003; ICSG 2012)

4.2.9 Additional criteria

The aspects described in the previous section cover the relevant areas of potential constraints for materials. Social and regulatory as well as geopolitical constraints are evaluated by means of governance stability, socio-economic stability, and potential for trade barriers. Technological constraints are evaluated by means of the companion metal fraction and the use of recycle material. And the increasing pressure for resource markets is addressed by means of an evaluation of the demand growth. All these indicators have medium-term relevance and were identified as appropriate for addressing the supply risk associated with materials. However, additional indicators exist that may affect supply risk. These indicators and reasons for excluding them in the current assessment are described in the following bullets:

- Mining from brine is generally easier than open pit or underground mining, and developing an underground mine requires more time than developing an open-pit mine. However, the differences are not significant enough for being included into an indicator. No evidence could be found, that open pit and underground mines differ significantly with regard to the time of exploitation. Regulatory requirements require most time when setting up mines and this generally depends rather on the regulatory and legislative framework of a country and not on the different materials as such. Different mining methods are more interesting with regard to the resulting environmental impacts.

- Excessive price volatility can have severe impacts on consumers and can create difficulties for industry sectors dependent upon the resource as input or output. Thus, when assessing the availability of resources for products, price volatility can be of relevance. However, price volatility is not further addressed in this dissertation due to the limited significance of prices to indicate scarcity (see Section 1.4).
- Substitution is often mentioned as a possible solution for resource scarcity. There is always the possibility of finding an alternative material to provide the required functionality (Graedel et al. 2014). However, many questions arise with regard to substitutes: is the substitute economically feasible? Is the substitute of equal quality? Is the substitute socially acceptable? Is the substitute environmentally acceptable? (see also Graedel and Klee 2002). For addressing substitution the complexity of the system needs to be considered. Substitution can occur on the elemental level, substituting a specific element by another in a particular product (Kleijn 2012). Substitution of an element always depends on the function of the element, but also on the specific technology an element is used in. Only because *copper* and *aluminum* have good electric conductivity does not mean that *aluminum* can substitute *copper* in all applications. Furthermore, new supply challenges are created through substitution (Hagelüken and Meskers 2010). Potential substitutes might be associated with even higher supply risks, rendering the inclusion of this indicator in the assessment of supply risk as questionable. Furthermore, substitution can also occur with regard to a specific function. Whether, certain functions are still required in the future and thus the need of resource to fulfill this function will persist is hard to determine. In this context, some materials will become more important over time and others less (Kleijn 2012; Wernick 1996). However, such interrelations are hard to determine and excluded from further analysis in this work.

In the next section, the methodological framework of the new model introduced in this paper is described and the thresholds as applied in the context of this dissertation are defined.

4.3 The economic resource scarcity potential: impact categories and methodology

For the assessment of economic resource availability the discussed criteria are transferred into impact categories which are described by characterization models using an analogy to LCA and current life cycle impact assessment (LCIA) methodology. In Table 4.3, an overview of the categories and corresponding category indicators as assessed in this work is presented (based on the analysis conducted in the previous section). While some indicators can be used directly (e.g., demand growth) as they are related to the materials as such, other indicators are related to the situation in the different countries of production. Thus, the country specific values need to be weighted by the respective production in the country to obtain an average value for the different materials. The indicator values for the different materials (i) are determined by means of the sum of the risk indicators (R) weighted by the share of a country (c) in the global production of the material. R_c can for example depict the governance stability of country *c* based on WGI data (see Eq. 7).

$$\text{indicator value}_i = \sum_{c=1}^{n} (S_{c,i} * R_c) \qquad \text{(Eq.7)}$$

Table 4.3: Overview of impact categories and indicators

Impact category	Description	Category indicators
Reserve availability	Depletion time (displaying current production technologies)	Reserve-to-annual-production ratio
Recycling	Recycled content of a resource	New material content (%); data as published by (UNEP 2011c)
Country concentration reserves	Reserve concentration to certain countries	HHI – index is calculated by squaring the market share of each company or country with regard to the production or reserves (USGS 2014a) and the summation of the results ; approaches zero when activities are distributed among a large number of companies or countries and reaches its maximum, 1, when reserves are located in only one country or production is taking place by only one company (starting from 0.15 concentration of activity exists) (DOJ and FDT 2010)
Country concentration mine production	Concentration of mine production to certain countries	
Company concentration mine production	Concentration of mine production to certain companies	
Governance stability	Stability of governance of producing countries (mine production)	WGI – including key dimensions of governance (The World Bank Group 2012) (in this work an aggregated indicator is used, based on three of the published dimensions that show only very low correlation: voice and accountability, political stability and absence of violence and government effectiveness; aggregation is based on equal weighting)
Socio-economic stability	Human development of producing countries (mine production)	HDI – combining indicators of life expectancy, educational attainment and income; indicator as published by UNDP (2011)
Demand growth	Increase of demand (past and future)	Percentage annual growth based on past systematics (for basic industrial metals) and future demand scenarios (driven by future technologies) (see Angerer et al. 2009a and Rosenau-Tornow et al. 2009)
Trade barriers mine production	Raw materials underlying trade barriers	Percentage share of mine production under trade barriers; based on data as published by BDI (2010)
Companion metal fraction	Occurrence as companion metal within host metal ore bodies	Percentage of production as companion metal – host metals are copper, aluminum, iron, rare earths, nickel, zinc, lead, magnesium, titanium and tin. Based on data by Haglüken and Meskers (2010), Reuter et al. (2005) and Erdmann and Behrendt (2010.

As introduced in Chapter 2, the evaluation of the different indicators to determine the associated supply risk is conducted by means of a distance to target method. In this regard, the individual indicator results are linked to a threshold. All indicator values are scaled to the range 0 to 1. When needed, order is inverted, such that a higher score corresponds to a high risk (similar to existing methods within LCA).[30] The results of this weighting are subsequently linked to the material inventory of the product. The resulting impact factors (I) are a function of current indicator values and the thresholds above which high risk of supply is expected. These factors are calculated for each material (i) and each impact category (j) (see Eq. 8).

$$I_{ESPi,j} = Max\left\{\left(\frac{\text{indicator value}_{i,j}}{\text{threshold}_{i,j}}\right)^2 ; 1\right\} \qquad \text{(Eq. 8)}$$

To avoid compensation during further aggregation of impact factors, no values below "1" are permitted in the assessment. Category indicator results (impact factor x LCI) give an indication about the magnitude of the risk (exceeding of threshold related to the amount of the resources). However, only a comparison of different resources can provide a meaningful estimation of associated supply risks and a basis for decision-making. For that purpose and for comparison with conventional resource assessment methods the different impact categories can be combined to a single *economic resource scarcity potential* (ESP) for each resource, enabling a ranking of overall risk scores. For calculation of the ESP impact factors are aggregated using multiplication to reinforce risks (see Eq. 9). A summation of factors would lead to the same ranking but the relative differences of results would be smaller. As this model will be linked with an LCI that might be dominated by few resources impact factors need to have a significant margin, so results are not determined only by the specific quantity of resources used.

$$\mathrm{ESP}_i = \prod_j \left(\mathrm{I}_{i,j}\right) \qquad \text{(Eq. 9)}$$

All impact factors are weighted equally during aggregation (see also Chapter 2.3). This approach can of course be modified as weighting might prove useful with regard to an emphasis of individual aspects or to avoid overvaluation of aspects.

As highlighted in Chapter 2, the results are highly dependent on the definition of the threshold. The risk threshold provides the advantage of an easy interpretation of results. A threshold above which supply risk is expected is defined for each category indicator. The supply risk for the individual resources is then calculated based on the respective distance to this threshold. In Table 4.4 an overview of thresholds used for determining the economic supply risks are given. The system under study in this paper is the average "global economy" and supply risks need to represent average global values. Thresholds are defined based on thresholds inherent to the different indicators or a general perception of risk in literature and current best practice in industry (Daimler AG 2012; DOJ and FDT 2010; Graedel and Klee 2002; Oryx Stainless 2012; The World Bank Group 2012; UNDP 2011). Graedel and Klee (2002) for example state that resource availability should be planned so that existing resources will last 50 years at current rates. This allows time for substitution of other resources or the development of alternative ways of meeting the needs that are served by the

[30]In the context of using a distance to target approach, indicator values do not need to have the same scale. However, for better representation and easier implementation of the indicator values, this scaling was conducted. An overview of the indicators values is provided in Appendix III.

resource consumption. To uncover all potential risks thresholds are selected which are not easy to attain (resulting in a high distance to the targets).

Table 4.4: Determination of thresholds (exemplary, as used in this study)

Indicator	Threshold[1] & risk
HHI	low < 0.15 < high
WGI[2]	low < 0.30 < high
HDI	low < 0.15 < high
Demand growth (%)	low < 0.01 < high
Production under trade barriers (%)	low < 0.25 < high
New material content (%)	low < 0.50 < high
Companion metal fraction (%)	low < 0.20 < high
Depletion time	low > 50 > high

[1]If not indicated otherwise, thresholds are based on data by Daimler AG (2012), DOJ and FDT (2010), Graedel and Klee (2002), Rosenau-Tornow et al. (2009), The World Bank Group (2012), and UNDP (2011). [2]Target is determined based on the average value of the European Union.

As already described in the introductory chapter of this work, thresholds are highly system specific: An organization, with a large product portfolio and frequently changing products would evaluate the risk of supply disruption as less critical than a company with few products and very long development and production life spans (e.g., vehicle production). Products with long service lifetimes require stable availability of a required set of resources (Graedel and Erdmann 2012). Thus, even though vulnerability to supply disruptions is not included as a dimension in this work, it is considered implicitly by means of the system specific determination of thresholds and perception of risk.

Ultimately, the choice of thresholds is a value choice. Results of the aggregated ESP are highly sensitive to the choice of impact categories and indicators as well as to the definition of the risk-threshold. Results of the assessment are system-specific and interpretation or comparison of results outside the system has little informative value. The assessment should not be regarded as fixed, situations should be regularly monitored and indicators have to be updated and thresholds readjusted (see also Graedel et al. 2012a; Rosenau-Tornow et al. 2009).

4.4 Results

A portfolio of 17 metals is selected based on data availability and also reflecting conducted case studies (see Oryx Stainless 2012; Schneider et al. 2011). Risks need to be assessed specifically for the different materials and many of the assessed indicators should be considered at several stages of the supply chain. Economic constraints can occur at any production stage (e.g., mining, refining or distribution). A low risk at one stage of the supply chain does not compensate high risks at other stages. However, for the time being, different supply chain levels are not considered due to limited data availability. Focus of this section is on the assessment of risks associated with the mining stage of different materials. The assessment allows a first insight and ranking of the different materials.

In Figure 4.8 the results of the ESP_{global} are presented (normal and logarithmic scale). The results are based on a fictional LCI, consisting of “1kg” of each metal. The supply risk assessed by means of the ESP_{global} is a dimensionless quantity. The magnitude of the ESP_{global} results is high and any exceeding of the threshold implies a potential risk. Thus, results are also presented using a logarithmic scale to uncover the risk of all assessed metals. Based on the aggregated ESP_{global} results presented in Figure 4.8 the metals can be ranked according to their risk.

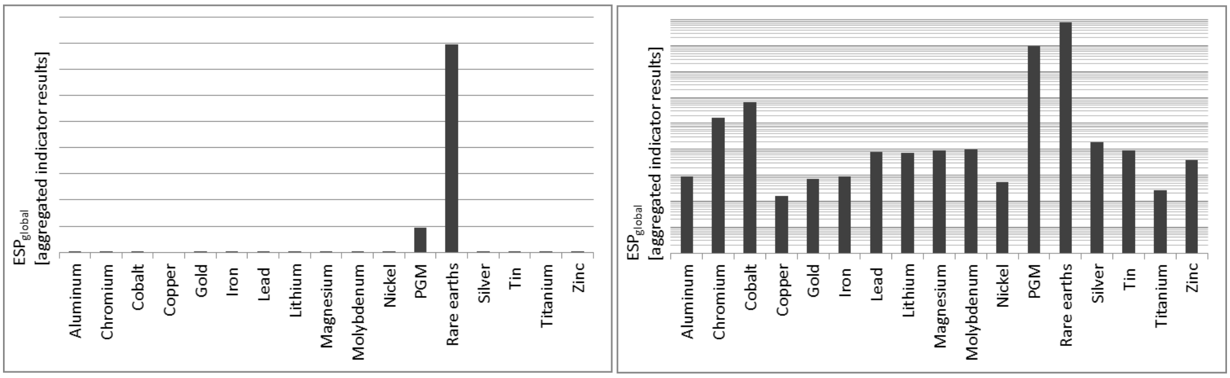

Figure 4.8: ESP_{global}, normal scale (left) **and logarithmic scale** (right)

Resources delivering the highest ESP_{global} are associated with the highest supply risk and thus a potential need for action. *Rare earths* for example show a high supply risk in several categories resulting in potential constraints in resource supply. Similar results are found for *PGM*. Contrary *copper* and *titanium* are associated with low overall supply risks. For a changing resource portfolio other metals could be identified to bear the highest risk.

To further test and discuss validity of the proposed approach results are compared qualitatively with supply risks identified in other studies (see Table 4.5). For this qualitative comparison the divergence from the threshold in relation to the maximum possible values for individual impact categories is used as a basis. Resources with overall high divergence from these targets are evaluated as risky. For all approaches, similar results are obtained. Deviations in results can be explained by the system under study, the choice and number of criteria and indicators or the temporal reference. Inclusion of additional indicators can increase or decrease overall supply risk for certain resources in comparison to the assessed resource portfolio. Within the ESP assessment, *nickel* has a lower relevance than in the study by Erdmann and Behrendt (2010) which could be caused by the consideration of additional categories like trade barriers that lower the relative supply risk of *nickel* in comparison to other resources in the assessed portfolio (see impact category results displayed in Figure 4.9). Likewise, *silver* for example is evaluated as less risky by the European Commission (2010) as only four indicators are considered, not including indicators where *silver* is associated with high supply risk (e.g. companion metal fraction or stability of producing countries). Low and high risk areas are only vaguely defined in these studies. A small shift in one of the indicators may for example result in an increase in overall supply risk and a shift from a low to a high risk area (see, e.g., *chromium* in the study of the European Commission (2010a)). While the ESP has a global focus, other studies assess resource availability for the European Union (European Commission 2010a) or Germany (Erdmann and Behrendt 2010). However, as supply risk is assessed by means of similar criteria within the different studies, the system perspective does not have an important effect on the results.

Table 4.5: Qualitative comparison of supply risk as determined in major studies[1]

Resource	**EU study (4)[2]** (European Commission 2010a)	**Yale studies (6)** (Nassar et al. 2012; Nuss et al. 2014)	**IZT study (6)** (Erdmann and Behrendt 2010)	**JRC (4)** (Moss et al. 2011)	**ESP_{global}[3] (10)**
Aluminum	low		low		low
Chromium	low	medium	high		medium
Cobalt	high		medium		high
Copper	low	low	medium		low
Gold		low			low
Iron	low	low	low		low
Lead			low		low
Lithium	low		medium		medium
Magnesium	low		low		medium
Molybdenum	low		medium	low	medium
Nickel	low		medium	low	low
PGM	high		high		high
Rare earths	high		high	high	high
Silver	low	high	high	medium	medium
Tin			high	medium	medium
Titanium	low		low		low
Zinc	low		medium		medium

[1]Studies are selected based on transparency of results. [2]Number in brackets indicate the number of indicators used to determine the supply risk. [3]Basis for this qualitative evaluation is the summarized divergence from the threshold value in relation to the maximum possible value across all impact categories (%), background information is provided in Appendix III.

The comparison verifies that ESP_{global} delivers a valid method and a good basis to comprehensively assess the supply risk associated with different resources. Results as displayed in Figure 4.9 should be regarded as a basis for an analysis of individual impact category results of ‘risky metals’ to identify hotspots and to develop appropriate strategies for risk mitigation. Availability of resources differs significantly when economic aspects are taken into account rather than geologic depletion. Detailed assessment of economic criteria influencing resource availability on a product level can be essential to prevent disruptions within the supply chain and help to identify “hotspots” and risks associated with industrial resource use.

In the next section additional issues are discusses with regard to the consideration of secondary materials, the sensitivity of the results to the choice of thresholds and the relevance of additional supply chain stages.

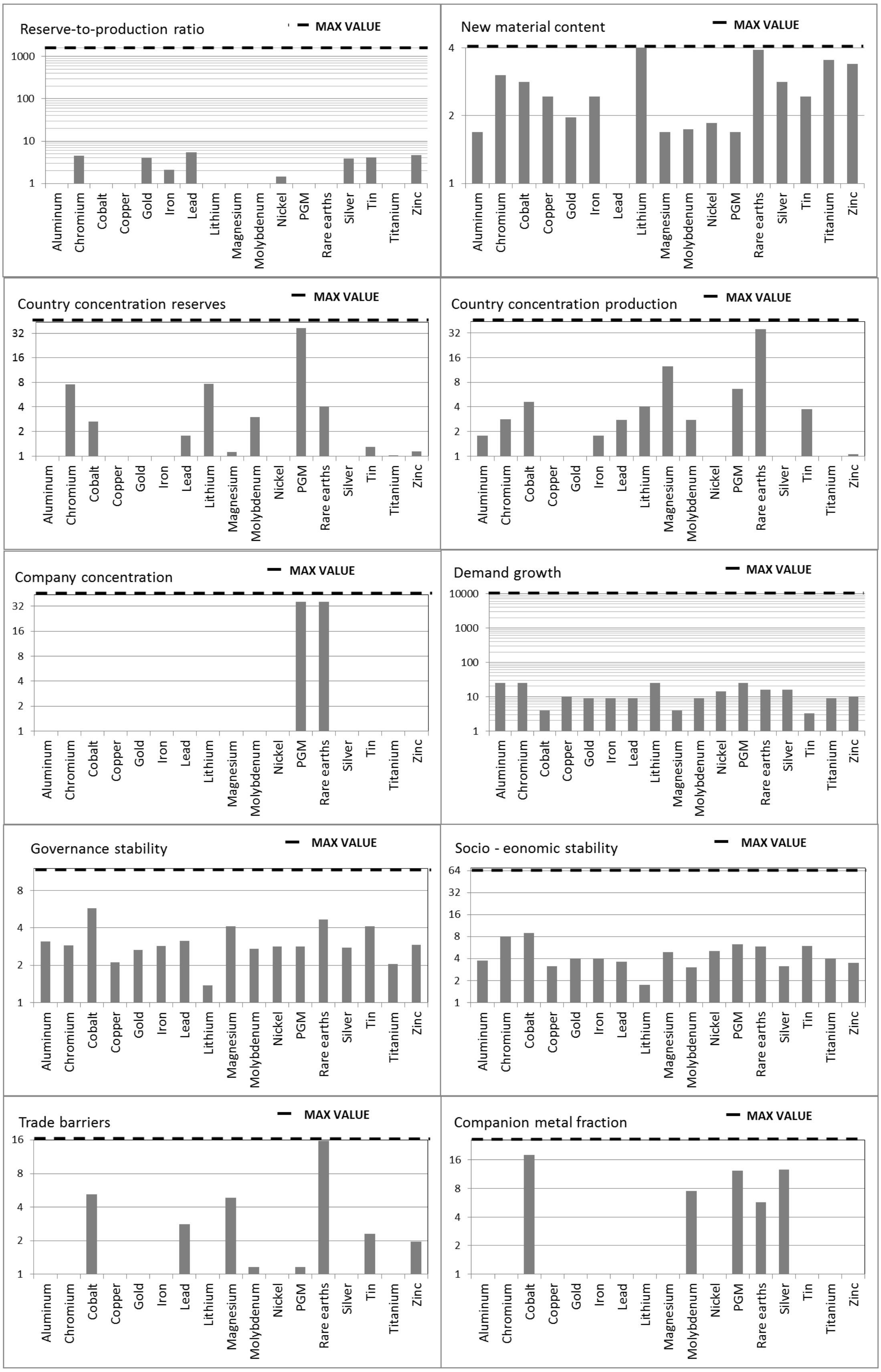

Figure 4.9: ESP$_{global}$ – Category results in relation to maximum risk value (maximum value is indicated by a black dashed line; values below "1" are associated with no supply risk)

4.5 Additional considerations

In addition to the assessment of primary resource availability, future studies need to consider a differentiation of primary and secondary resources. Evaluated criteria mostly refer to primary resource supply only and some of the developed impact categories are not relevant if only recycled material is used. However, secondary material, so far considered as a measure to delay the depletion of primary metal resources, may underlie similar restriction as primary material supply. The sequence for secondary materials is associated with similar constraints than primary material. The supply chain involves for example the separation of the metals in the discards or metallurgical processes that can take place in different countries. Thus, a more comprehensive assessment is needed and primary and secondary materials should be analyzed independently from each other. Exemplarily, the availability of relevant primary and secondary materials for the production of stainless steel is evaluated. In Figure 4.10 the results of the ESP_{global} for a typical material portfolio for the stainless steel industry are presented focusing on *chromium*, *iron*, *nickel* and *stainless steel scrap* (values for scrap are based on data published by Heinz H. Pariser 2011).[31] Supply risks associated with secondary production can differ significantly from the risks associated with primary materials.

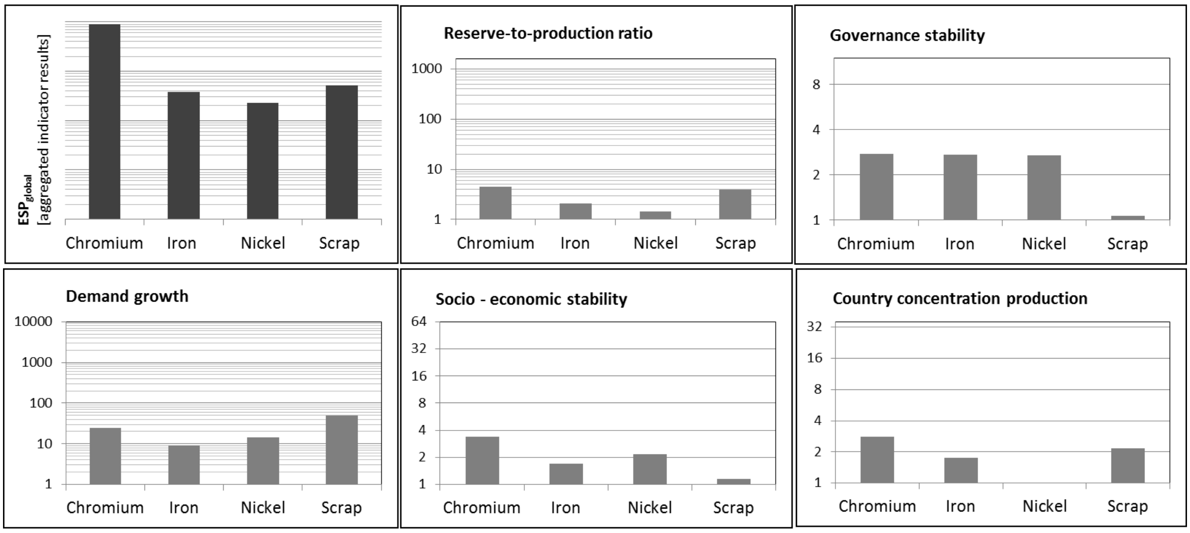

Figure 4.10: ESP_{global} – Primary vs. secondary material, aggregated and individual indicator results

According to this analysis, *chromium* is associated with the highest economic supply risk. However, surprisingly the availability of scrap seems to be more constrained from an economic perspective than the (primary) supply of *iron* or *nickel*. Scrap materials and recycling facilities are often concentrated in few countries, and the demand for stainless steel scrap has been is increasing strongly over the past decades. Thus, the use of secondary materials might not always be better – at least from an economic supply risk perspective.

As described in the introductory section of this chapter, risks can occur along the entire supply chain of materials. For sustainable resource management, all life cycle stages, from

[31] For the assessment of primary vs. secondary material the following impact categories are considered: recycled content, governance stability, demand growth, country concentration production, socio-economic stability.

resource extraction through production and manufacturing to use and end-of-life treatment need to be analyzed (Finkbeiner 2011). Each stage of the supply chain has to be assessed. Currently, the main limiting factor for the assessment of the entire supply chain is data availability. In Figure 4.11 the country concentration associated with the mining, smelting, and refining of *cobalt* and *copper* are displayed, to highlight the potential difference within the supply chain stages and the need to uncover all potential bottlenecks. In this specific case, mining is associated with higher country concentrations, and accordingly a higher supply risk. However, the bottleneck to material supply can be anywhere in the supply chain. In further works, an assessment of other supply chain stages needs to be included to uncover all potential restrictions and risks associated with the supply of materials like *copper* or steel (e.g., over 70 % of the seaborne trade of *iron* is controlled by three companies only, resulting in high company concentration for traded *iron*; European Commission 2010a; UNCTAD 2012).

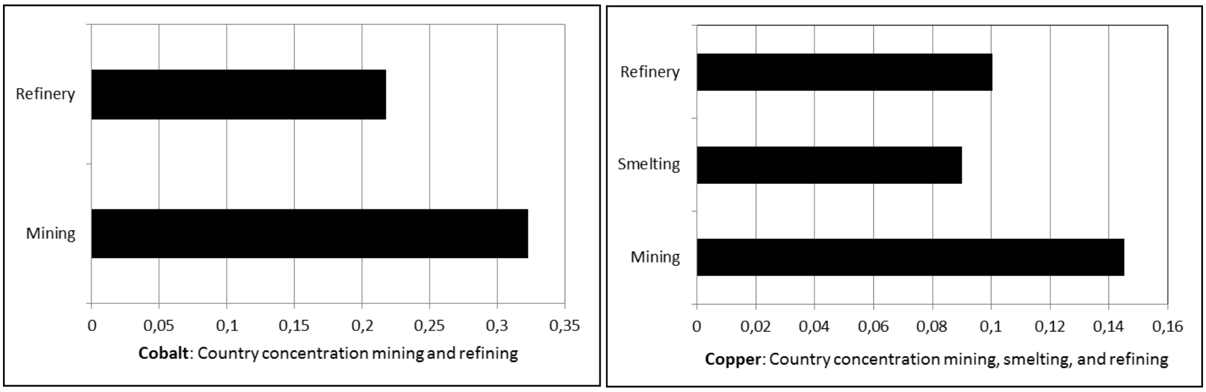

Figure 4.11: Country concentration at different supply chain stages (Edelstein 2013; Shedd 2013)

Supply risk assessment depends strongly on the perspective and the setting of the thresholds and can be adapted to company targets, national regulations, and so on. These thresholds can be different from company to company and from country to country and can refer to internationally set thresholds, or individual goals according to a general perception and best practices. In the following, the sensitivity of the ESP_{global} with regard to the defined thresholds is evaluated to highlight the relevance of the thresholds on the overall results. For this purpose, thresholds are defined depicting a more *conservative* and a more *unconcerned* point of view. In Table 4.6 the thresholds used as a basis for the sensitivity analysis are displayed.

Table 4.6: Determination of thresholds – Sensitivity analysis

Indicator	**Threshold & risk** ***conservative***	**Threshold & risk** ***unconcerned***
HHI	low < 0.10 < high	low < 0.20 < high
WGI	low < 0.10 < high	low < 0.40 < high
HDI	low < 0.10 < high	low < 0.20 < high
Demand growth (%)	low < 0.01 < high	low < 0.01 < high
Production under trade barriers (%)	low < 0.10 < high	low < 0.30 < high
New material content (%)	low < 0.25 < high	low < 0.75 < high
Companion metal fraction (%)	low < 0.10 < high	low < 0.30 < high
Depletion time	low > 100 > high	low > 30 > high

The ESP_{global} results according to the targets defined in the previous section and ESP_{global} results based on *conservative* targets are shown in Figure 4.12. The overall trend of the results is the same as previously evaluated supply risks. However, the overall risk as such increases due to the higher distance to the defined threshold (target). In the conservative approach also indicators that did previously not contribute to the supply risk do now present a risk. The ranking of materials experiences a slight shift. *Copper* for example is evaluated as more critical than *titanium* based on the conservative thresholds. Furthermore, in the comparison, *molybdenum* and *lead* are perceived as more critical than before. *Molybdenum* is associated even with a slightly higher supply risk than *silver*.

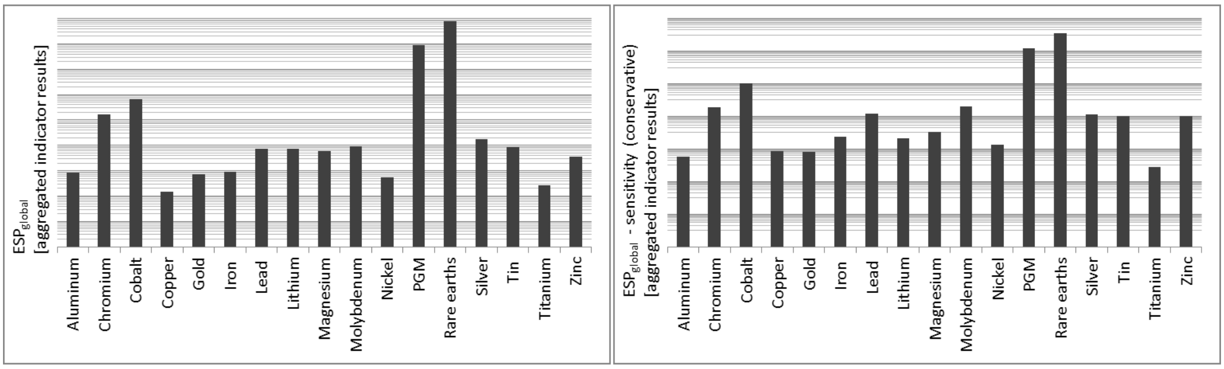

Figure 4.12: ESP_{global} (left) **vs. ESP_{global} – *conservative*** (right)

In Figure 4.13 the same comparison is shown, but this time comparing ESP_{global} as evaluated in the previous section and ESP_{global} based on an *unconcerned* perspective. Many indicator values previously showing a significant distance to the targets, are now displaying no, or significantly lower risks. The overall trend remains but the distribution of the supply risks at the lower "levels" changes (e.g., supply risk associated with *lithium* increases in comparison).

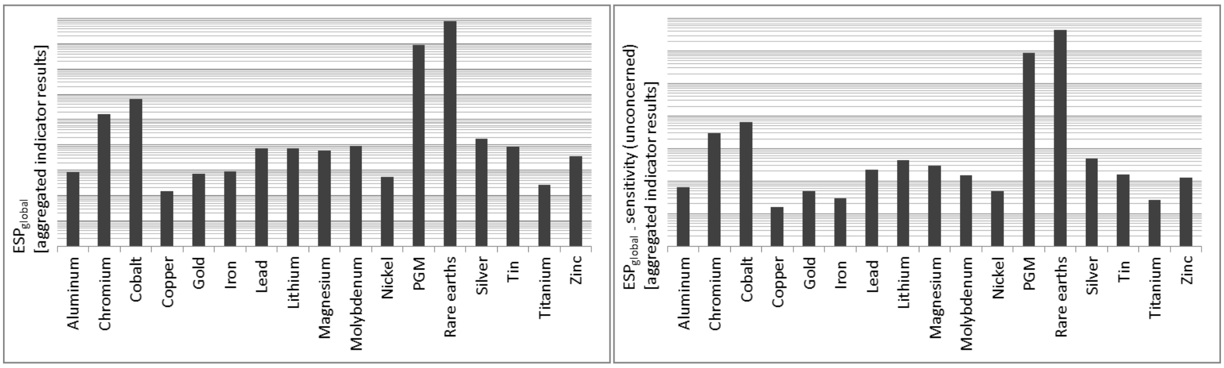

Figure 4.13: ESP_{global} (left) **vs. ESP_{global} – *unconcerned*** (right)

This analysis highlights the strong dependency of the results on the identified threshold. Definition of thresholds thus needs to be closely considered and ideally aligned with sustainability goals. Generally, a more conservative approach is recommended to avoid the negligence of bottlenecks within the supply chain.

5 ENVIRONMENTAL CONSTRAINTS TO RESOURCE SUPPLY – THE ENVIRONMENTAL RESOURCE SCARCITY POTENTIAL

Abstract

Environmental protection is relevant for sustainable development and environmental limits to resource supply will become increasingly constraining. Resource extraction is associated with several environmental impacts. Measures taken by companies or governments to reduce environmental impacts can indirectly affect resource availability and environmental pollution might constrain the access to certain materials.

The aim of this chapter is the development of a methodology for the determination and assessment of resource provision capability from an environmental angle. The evaluation is based on existing impact categories and characterization models within LCA, but environmental impacts are transferred to an environmental supply risk.

A portfolio of 20 metals is evaluated under consideration of the acidification potential (AP), the global warming potential (GWP) and the ecotoxicity potential (EP) associated with the extraction and production of primary metals. By evaluating the different characterization results by means of an environmental "threshold-level", environmental risk scores are determined. By means of the aggregation of different risk scores, the environmental resource scarcity potential (EnSP) is defined. The developed model enables a comparative evaluation of the environmental risk associated with different materials. From an environmental perspective, gold is associated with the highest supply risk, followed by platinum and palladium. Aluminum, iron, and tin seem to be rather uncritical in the comparison. However, results have to be seen in the context of existing shortcomings with regard to databases and methodologies to measure environmental impacts.

The assessment in this chapter allows for a comparative analysis of resource provision capability under consideration of potential environmental constraints to resource supply. By including environmental risks associated with materials into decision making a contribution towards sustainability assessment is achieved.

5.1 Environmental constraints to resource supply: an overview

Measures might be taken by governments (countries, regions) or stakeholders with the intention of protecting the environment. Such measures can indirectly affect resource availability as they might constrain the access to certain materials (see, e.g., European Commission 2010a). Aim of this chapter is to evaluate the environmental supply risk associated with different materials and to establish a basis for decisions in compliance with sustainable development. In this first section, relevant environmental impacts associated with abiotic resource provision are identified and discussed, as a starting point for further analysis.

Mining can have significant impacts on the environment, at the site where rock is extracted and on its surroundings as a result of the need to store or dispose large quantities of wastes (Rankin 2011). The interventions caused by mining are multiple. Blasting off mountaintops has severe visual impacts on the landscape and leads to the destruction or disturbance of natural habitats and can affect soil health or biodiversity (Acton et al. 2011; Bernhardt et al. 2012). Local communities can be affected due to the loss of farmland or recreational space and increasing levels of noise or traffic (Morrison 2006). Environmental interventions associated with mining activities might violate land claims of indigenous people and may be in conflict with cultural heritage (Rankin 2011). Furthermore, mining greatly impacts soil and aquatic ecosystems (Acton et al. 2011; Rankin 2011). Large quantities of water are used in the minerals industry and water might be consumed or contaminated. *Lithium* for example is produces in arid territories. In Chile's Atacama salt flats, mining consumes, contaminates and diverts scarce water resource away from local communities by evaporating salt brines which uses large quantities of the area's fresh drinking water (Hollender and Schultz 2010; Zacune 2013). This has effects on livestock and crop irrigation, decreases the availability of water for human use and has effects on communities and ecosystems. Furthermore, effluents generated by the metals mining industry can contain toxic substances which can pose significant health and ecological risks (Azapagic 2004). All these aspects can effectively constrain the availability of resources as they hinder sustainable development and have negative effects on human wellbeing and ecosystems and need to be reduced and avoided. In the context of addressing the environmental constraints to resource supply, in this chapter only impacts on ecosystems are addressed. Impacts of mining on local communities or cultural heritage are caused by the environmental intervention but are of social nature and need to be assessed under the framework of the social dimension of resource provision capability (see Chapter 6).

Water and soil pollution, destruction of landscapes, disposal of waste rock, and particulate matter are named as common environmental impacts of mining and mineral processing operations(see, i.a., Azapagic 2004; Humphreys 2010; Lindeijer et al. 2002; MEND 2009; Mudd 2010; Norgate and Haque 2010; UNEP 2013; Wäger et al. 2011). In general, environmental impact can occur during the extraction or processing of resources and during the use, recycling and disposal of materials (Steinberger et al. 2010). In Figure 5.1 an overview of the different "types" of environmental impacts associated with the extraction and use of abiotic resources is displayed. For determining potential resource scarcity induced by environmental constraint, different environmental impacts associated with the provision of abiotic resources need to be specified and evaluated. The mining, extraction and processing stages are often very energy intensive, causing fossil-fuel-related emissions (Petrie 2007; UNEP 2010a). Furthermore, sulfur dioxide (SO_2) can be produced at metal production facilities that process sulfide ores (e.g., *copper*, *nickel*, or *silver*) (Reuter et al. 2005). From a life cycle perspective, emissions can also occur during the use of resources. Environmental impacts of fossil fuels for example occur to a large share during the consumption (burning) of these. However, in line with the earlier definition of the scope of this study, impacts during the use-phase and end-of-life phase are excluded from the assessment and only environmental impacts associated with the resource provision level are examined.

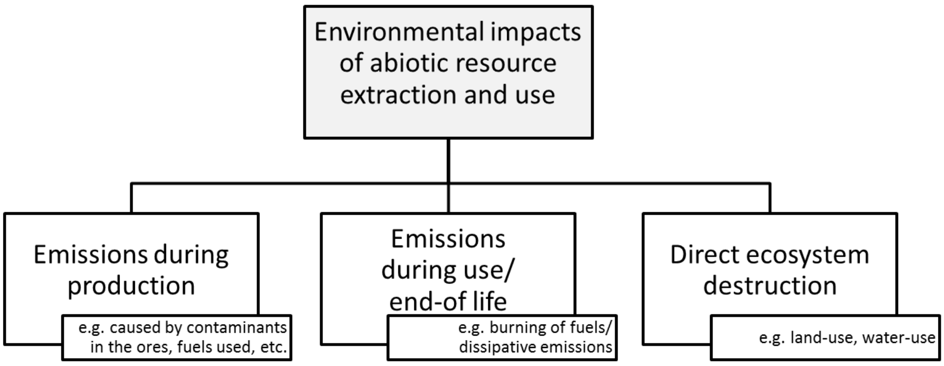

Figure 5.1: Environmental impacts – extraction and use of abiotic resources

The focus of this chapter is on the evaluation of metals. In Table 5.1 an overview of the most important impacts of primary metal production is provided, considering mining and mineral processing, smelting and refining. Environmental impacts can occur at the site of extraction, during processing, later in the supply chain, or at the product level (retrospectively). The quantification of many of these environmental impacts is difficult and limited data is available. Ideally, for a comprehensive assessment of environmental constraints to resource supply, all impacts should be considered.

Table 5.1: Relevant impacts of mining and extraction processes for metals (based on UNEP 2013)

Production stage	**Inputs**	**Emissions**
Mining and mineral processing operations (e.g., drilling, blasting, crushing)	Energy (diesel, electricity), chemicals[1], water, land	Particulates, vehicle emissions, greenhouse gases, noise, toxic substances[2], (waste)
Smelting	Energy (diesel, electricity), chemicals, water	Particulates, sulfur dioxide, greenhouse gas emissions, toxic substances, noise
Refining	Energy (diesel, electricity), chemicals, water	Greenhouse gases, toxic substances

[1]Chemicals include explosives (e.g., ammonium nitrate/fuel oil) or reagents (e.g., lime, xanthate, sodium cyanide) [2]Toxic substances or hazardous waste can include sludge, oil and oil emulsions, acids and alkaline solutions, etc.

To quantify the different environmental aspects, this dissertation relies on existing methods and models. As highlighted in Chapter 2.3, one commonly used tool for assessing environmental impacts is LCA. For the assessment of environmental impacts of product inventories, LCA has proven valuable and is thus used as a basis for the assessment of resource provision capability from an environmental angle. As environmental assessment is already common practice for the evaluation of products, this work takes up existing impact categories and assessment methods. In order to specify the environmental risk associated with the different materials the environmental impacts of each material need to be assessed based on existing life cycle inventories (LCI) of material production and by means of existing environmental impact categories. However, many of the addressed aspects are hard to quantify and evaluation methods are currently missing. Some of the addressed aspects are covered in LCA, but with varying degrees of data availability and methodological development. While the assessment of air pollution is already common practice, no commonly agreed methods and inventory data exist for accounting for land-use, particulate matter, water use, noise or toxic emissions. In Table 5.2 an overview of different environmental impacts associated with resource extraction is provided discussing implementation and shortcomings in current LCA practice. Existing life cycle impact assessment methodologies do not suffice to account for all potential impacts associated with resource extraction. Impacts on the environment that are outside of current LCA practice cannot be evaluated properly and are excluded for the time being.

Table 5.2: Overview of relevant environmental impacts of mining and extraction

Aspect	Description	Implementation and shortcomings
Air pollution	Operation of the mines leads to releases of greenhouse gases and various air contaminants.[1]	The assessment of air pollution is common practice with LCIA and several impact assessment methods are available that are generally agreed on (even if discussion with regard to characterization models is ongoing).[2]
Land-use	Land-use is an important topic as mining activities can alter land-use patterns. Mining processes differ for the different abiotic resources. For example, mining methods are broadly categorized as surface and underground mining, depending mainly on the deposit type and depth. Land-use aspects of mining differ for open pit and underground mines.[3]	Currently, the impact category land use is hardly applied in LCA. One reason is the lack of a broadly agreed impact assessment method. Most of the existing methods are only adding up square meters, which do not adequately reflect losses of biodiversity or soil quality aspects. Lack of sufficient inventory data is another problem as for most of the existing methods, spatial inventory data is needed. Even though background data on square meter level is partly existing, databases are far from being complete.[4]
Particulate matter	Air quality impacts from mining are mainly caused by the release of airborne particulate matter.[5] Particulate matter refers to fine particles below 10µm of particle size, forming aerosols. The emission of particulate matter can have strong impact on human health.[6]	Many different impact assessment models are availability that address particulate matter. However, consistency is lacking and modelling aspects as well as comprehensiveness are still in need of further development.[7] Even though the inclusion of particulate matter is relevant for the environmental assessment of mining activities, existing models do not allow for a comprehensive and consistent analysis.
Water use	Water for processing ore can pose a constraint in the context of competing use and pollution.	Some consequences of water use, for example eutrophication or human- and ecotoxicity are sufficiently covered in LCIA by respective impact categories Additionally, several inventory and impact assessment methods were developed, describing various cause-effect chains on human health, ecosystems, and resources.[8] Since water scarcity is a local phenomenon, impacts of water consumption need to be assessed on a local level, too. However, obtaining accurate data on water use is difficult and appropriate models and methodologies are still in a development stage.
Noise	Noise can be regarded as ‘unwanted sound‘ which possibly affects human health, as it may, for example, impair cognitive abilities, cause sleep disturbance, increase the risk for heart diseases or lead to hearing impairments.[9]	Several methodologies for assessing noise are available, but a consistent framework and comprehensive inventory data are still needed. Thus, noise is not included in current environmental impact assessment.[10]

Aspect	Description	Implementation and shortcomings
Toxic emissions	Mining is often associated with the discharge of toxic substances.[11]	The discussion of the assessment of toxic emissions is far from being solved. General challenges encompass the absence of regionalized and inventory dependent characterization factors and lacking consistency in fate, exposure and effect evaluation. Beyond that, available models are not complete regarding the chemicals which are potentially relevant and neglect cumulative effects of chemicals.[12]

[1]see MEND (2009) [2]see, e.g., Guinée (2002) [3]see MEND (2009) and Durucan et al. (2006) [4]Curran et al. (2011); Mattila et a. (2012), Milà i Canals (2007) and Finkbeiner et al. (2014) [5]Airborne particulate matter can result from various activities, including blasting, crushing, loading, and hauling (MEND 2009) [6] Brunekreef and Holgate (2002) [7]see, e.g., Finkbeiner et al. (2014), Greco et al. (2007), Humbert et al. (2011), Pope et al. (2009) [8]see, e.g., Berger and Finkbeiner (2010) and Guinée et al. (2002) [9] Clark et al. (2006), Griefahn et al. (2006), van Kempen et al. (2002) [10]Althaus et al. (2009), Cucurachi et al. (2012), Meijer et al. (2006), Reap et al. (2008) [11]see, e.g., Brown (2002) [12]Finkbeiner et al. (2014)

In the context of the identified limits, this dissertation focuses on air emissions contributing to air, water and land pollution and related impacts. Emissions of greenhouse gases and acid gases have been identified as relevant and commonly accepted characterization methods are available (see also Azapagic 2004; European Commission 2011a; Zinc for Life 2013). Furthermore, ecotoxicity impacts caused by the release of toxic substances are assessed. Particulate matter and water and land use are not assessed further due to insufficient impact assessment methodologies and/or the lack of inventory data. In the following section the causal framework is outlined in more detail and the methodology for assessing the environmental risk to resource supply is introduced.

5.2 The environmental resource scarcity potential: cause-effect-relation and methodology

This section specifies the methodology for addressing potential environmental constraints to resource supply. The approach is oriented on the basic methodology described in Chapter 2 but further specified for the application in an environmental context.

Currently, environmental impacts of resource extraction are only addressed in connection to products. So far no link to the level of resource provision has been established. In complex products, materials as such often have only a negligible contribution to the overall impact (e.g., *lithium* as part of the lithium-ion battery or *rare earths* required for permanent magnets) and are not identified as a significant parameter during impact assessment (see, e.g., Buijs and Sievers 2012; Stamp et al. 2012). Thus, material choices are normally not made under consideration of the environmental impacts of primary material production and potential environmental constraints to resource supply are disregarded. In current models to assess resource availability in LCA, the extraction process is excluded from the availability assessment and only the environmental intervention *extraction* as such is considered, representing the removal of a certain quantity of a resource from nature and their decreasing availability (Lindeijer et al. 2002). However environmental interventions can indirectly affect resource provision capability. For example, environmental legislation or sustainable development goals may constrain the supply of certain materials as they strive to impede impacts on human health or ecosystems and affect production processes (see, e.g, Klinglmair et al. 2013). In Figure 5.2 the causal relationships in context of addressing environmental risks associated with resource provision are shown in more detail. The risks can originate from regulations or limits associated with the exploitation and extraction of natural resources or as a result from non-compliance with corporate goals or stakeholder demands (e.g., public rejection of tar sands leading to boycotts of companies that are ‘complicit’ in their production (Nuccitelli 2011; Nunez 2014)). With increasing environmental impacts the probability of such constraints along the supply chain increases as well. The risk is in general assumed to be higher, the higher the environmental impacts associated with the production of a certain material.

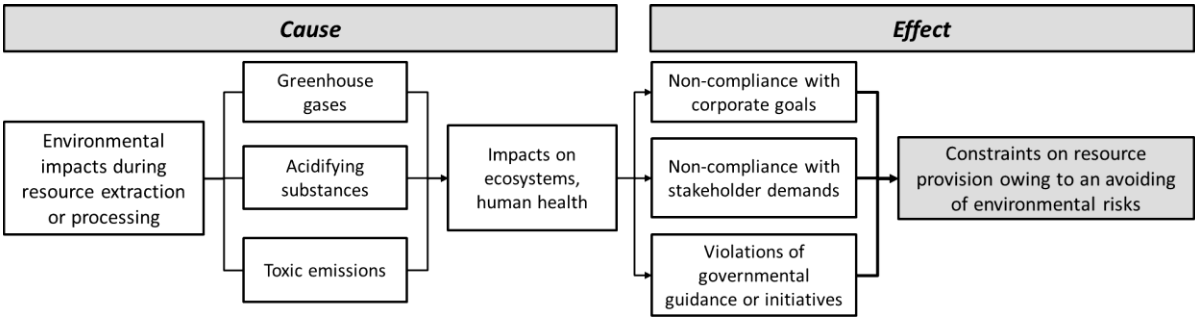

Figure 5.2: Cause-effect-chain – Environmental impacts and risks

As addressed in Chapter 2, the constraints associated with resource provision can occur at any stage of the supply chain and might be immediate or retrospective. Constraints can be imposed on a country-, corporate-, or consumer level and can occur at site of production or can be concerned with upstream processes.

For identifying risks associated with the continued supply of different resources current assessment practice delivers little informative value as no “risk” thresholds are included. This leaves little support for interpretation of the results. The relevance of target levels for interpretation of impact assessment results has been highlighted before (see, e.g., Jørgensen et al. 2014). In the context of assessing the environmental risk of resource supply, target levels are urgently needed. Environmental impacts as such will not constrain resource provision capability. Only when a certain level is reached (e.g., violation of air quality standards or corporate goals), environmental impacts pose a risk to continued resource supply. For the determination of the environmental risk to resource provision, results from the characterization as such are not sufficient but need to be put in relation to an environmental “risk-threshold” (see Chapter 2). The probability that the defined environmental impacts pose a constraint to resource provision capability needs to be calculated. Prior to weighting many studies suggest a normalization of the impact category indicator results (see, e.g., Dahlbo et al. 2013; Finnveden et al. 2002). However, in the context of the distance-to-target evaluation, normalization is not needed, as the relation between the actual value and threshold would not change if normalization would be applied preliminary.

For determining the environmental supply risk, impact factors (I) are calculated for each resource (i) and each impact category (j) and are a function of the category indicator results (C) and the threshold above which high risk of supply is expected (see Eq. 10). By squaring this ration the exceeding of the target value is weighted above proportional, emphasizing high risks. To avoid compensation during further aggregation of impact factors, no values below "1" are permitted in the assessment. The definition of an environmental threshold is not as straightforward as there are no thresholds inherent to the different impact categories. So far no data is available for making a general statement with regard to the level from which on environmental impacts pose a risk to further resource supply. Thus, the material associated with the lowest impacts in the respective impact category is chosen as a threshold value in this study with the aim to uncover all potential risk. This threshold can be seen as a best estimate. However, this choice needs to be reviewed with existing literature to avoid a reference to materials with very high environmental impacts, which could be misleading.[32] Future studies should customize this threshold for example to specific company or corporate strategies or emission targets and thresholds should be aligned to sustainability goals.

As displayed in Equation 10, the actual value is assessed in relation to the material with the lowest category indicator result in each of the addressed impact categories (C_{min}) (thus, results below "1" are not possible in this specific case).

$$I_{EnSPi,\,j} = Max\left\{\left(\frac{C_{i,\,j}}{C_{min\ i,\,j}}\right)^2 ;1\right\} \qquad \text{(Eq. 10)}$$

Resulting supply risk associated with resources is a dimensionless quantity determined exclusively by the ratio of the current indicator value to the determined threshold. Category indicator results (impact factor × LCI) give an indication about the magnitude of the environmental risk (exceeding of threshold related to the amount of the resources). For easy identification of potential environmental constraints, the different impact categories are aggregated to a single environmental risk indicator, the *environmental resource scarcity potential* (EnSP). The aggregation of different environmental impacts is not common practice in current life cycle impact assessment. However, in the context of uncovering potential environmental constraints to resource supply, the risk probabilities (increasing with high environmental impacts) need to be aggregated to enable a ranking of overall environmental supply risks and to provide a good basis for decision making. For calculation of the EnSP, impact factors are aggregated using multiplication to reinforce risks (see Eq. 11). As this model will be linked with an LCI that might be dominated by few resources impact factors need to have a significant margin, so results are not determined only by the specific quantity of resources used.

$$EnSP_i = \prod_j \left(I_{EnSPi,\,j}\right) \qquad \text{(Eq. 11)}$$

[32] The ranking within the material portfolio would still enable a statement with regard to the relative supply risk (e.g., material A is associated with a higher environmental supply risk than material B). However, a low identified supply risk in this context would be no evidence for an actual low supply risk as the "threshold material" would already be associated with high environmental risks.

Aggregation, as used in this work, implies equal weighting of individual impact factors. This approach can of course be modified as weighting might prove useful with regard to an emphasis of individual aspects or to avoid overvaluation of aspects. The comparison of different resources on the basis of the EnSP can provide a meaningful estimation of associated supply risks and a basis for decision-making. As indicated earlier in this chapter, emissions of greenhouse gases, acidifying substances as well as toxic emissions during metal production are assessed. Furthermore, in this work energy use is a crucial factor with global implications (UNEP 2013). Due to the high energy demand needed during metal production the primary energy demand (PED) is also evaluated as part of the environmental evaluation.[33] In Table 5.3 an overview over the selected categories is provided. The selection is based on the applicability and availability of impact assessment methods and expected relevance of the categories and should not be seen as exhaustive. For a more realistic evaluation of environmental supply risks the assessment of a broader set of impact categories is proposed for the future.

In the next section the results of the impact assessment and the calculation of the EnSP are presented.

Table 5.3: LCIA categories and indicators

Categories	Description	Unit	Reference
Primary energy demand (inventory category)	A measure of the total amount of primary energy needed	MJ, net cal. value	PE International (2013)
Climate change	Global warming potential (GWP) – A measure of greenhouse gas (GHG) emissions such as CO_2 and methane	kg CO_2-e.	IPCC (2006), 100 year GWP is used
Acidification	Acidification potential (AP) – A measure of emissions with acidifying effects on the environment	kg SO_2-e.	Guinée et al., (2002) factors updated in 2010
Ecotoxicity	USEtox ecotoxicity potential – A measure of effects on freshwater ecosystems	CTUe[1]	Rosenbaum et al. (2008)

[1]The characterization factor for aquatic ecotoxicity impacts is expressed in comparative toxic units (CTUe), an estimate of the potentially affected fraction of species integrated over time and volume, per unit mass of a chemical emitted (Rosenbaum et al. 2008).

5.3 Results

In this section an overview of potential environmental impacts associated with material production is presented, including the categories identified in the previous section. A portfolio of 20 materials is assessed, based on a mass of "1kg"of each metal (hereby consistency with the material portfolio in Chapter 4 is aspired).[34]

[33]The ferrous and non-ferrous metal industry for example is responsible for approximately 20% of all industrial energy use worldwide (IEA 2010).

[34]No data on the environmental impacts of *chromium* is available in existing databases. Furthermore, *neodymium*, *terbium*, *ytterbium*, and *samarium*, as well as *platinum* and *palladium*, are evaluated instead of the subordinate group.

Contrary to the method for addressing the economic dimension of resource availability, characterization methods for determining environmental impacts associated with resource use are used as a basis for the assessment in this chapter. Thus, weighting by means of the distance-to-target method is based on the category indicator results. This section consists of two main parts:

- Firstly, life cycle impact assessment results are presented for the identified impact categories and problems and challenges are identified.
- Secondly, the results are weighted according to the distance to target approach as specified in Chapter 2 and the results are displayed and aggregated into the EnSP.

Background data (LCI-data) for the evaluation are taken from databases available in GaBi 6 (PE International 2013). Hereby, preferably global data are used. If none are available, European or national data are chosen.[35] For the assessment, primarily data provided by PE International are used, however, LCI data for *molybdenum*, *neodymium*, *lithium* and *cobalt* had to be retrieved from ecoinvent (Classen et al. 2007; PE International 2013).[36]

As a first step, the primary energy demand associated with the production of the different materials (per kg) is evaluated (indicated in MJ and including renewable and non-renewable resources). Energy use of primary metal production was identified as a major cause of impacts and the energy demand for the production of the different materials needs to be assessed in the context of "uncovering" potential risks to supply. In Figure 5.3 the primary energy demand (PED) associated with the assessed material portfolio is presented. *Gold*, *palladium* and *platinum* are associated with highest primary energy demand (exceeding the graph by 7 to 33 orders of magnitude).

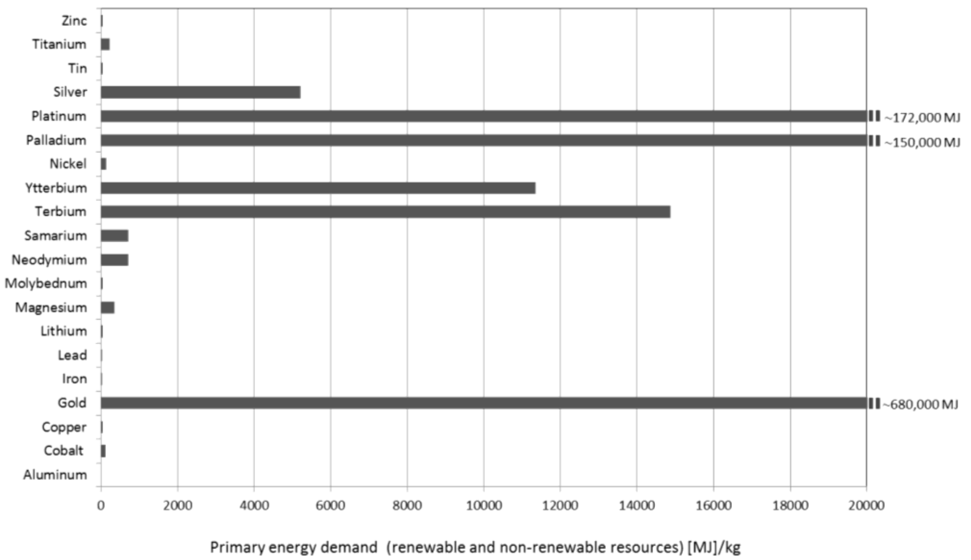

Figure 5.3: Primary energy demand (PED) (renewable and non-renewable resources, net cal. value [MJ]). Horizontal axis ends at 20,000 MJ.

[35]For the production of *rare earths* for example only LCI-data for China are available in the existing databases. As this however displays the actual situation it does not compromise the evaluation of the global average risk.

[36]As a basis of the calculations best available data is chosen. However, following adjustments have to be made: An *aluminum* ingot is used as the basis for the evaluation of *aluminum* and instead of *iron* a steel sheet is used as basis (but low content of alloying elements).

As a second step, the environmental impacts for the production of "1kg" of each material are assessed. In Figure 5.4 the global warming potential (GWP) is displayed. Again, *gold*, *platinum* and *palladium* are associated with the highest impacts.

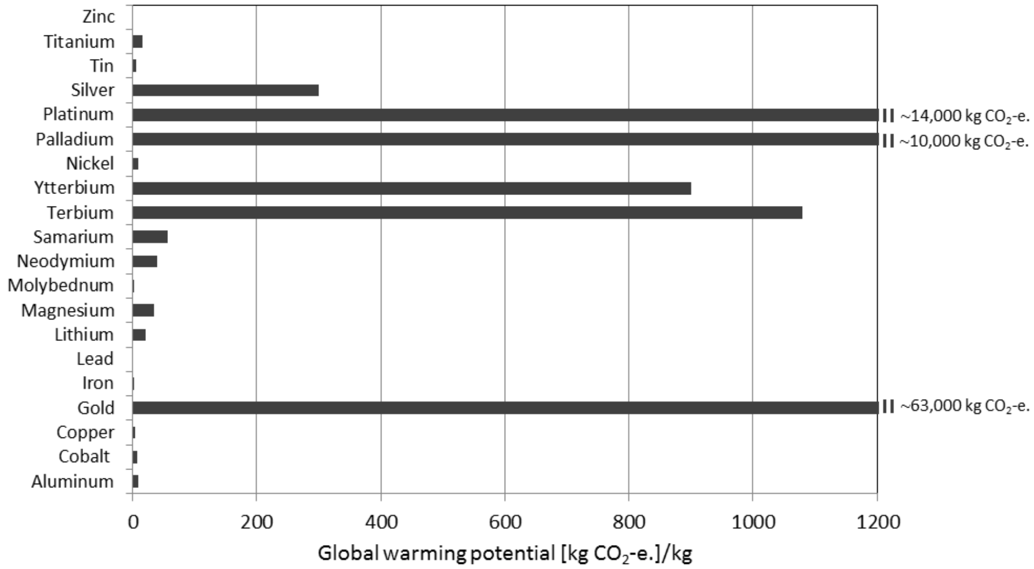

Figure 5.4: LCIA results - Global warming potential (GWP) (according to CML-IA). Horizontal axis ends at 1200kg CO_2-e.

Greenhouse gas emissions occur mainly due to the use of energy during metal extraction and refining (mostly diesel and electricity). Consequently, there is a strong correlation between the PED and the GWP of the different metals (R^2=0.99) (see Figure 5.5 – the correlation persists also if a normal scale is used) (see also Berger and Finkbeiner 2011). Hence, the evaluation of one of these values is sufficient for determining the environmental impacts of resource extraction and to avoid double counting. Subsequently, only GWP is used as a reference for the calculation of the EnSP.

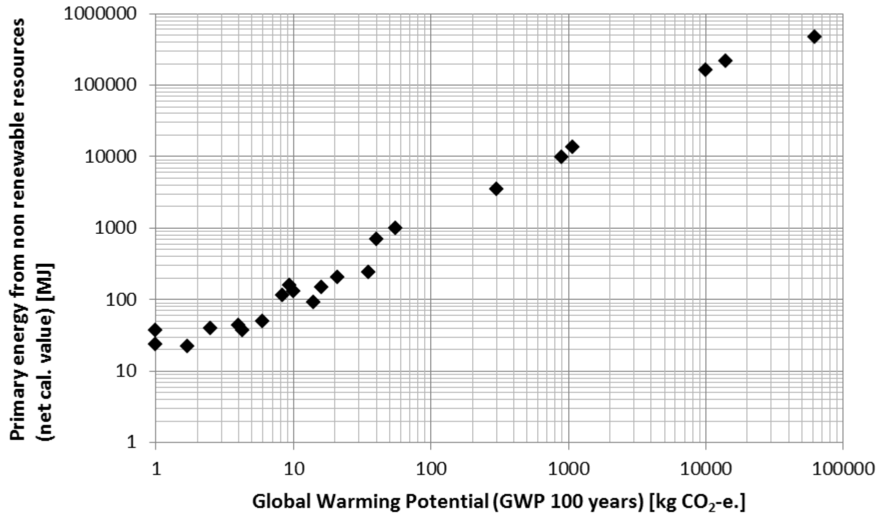

Figure 5.5: Correlation analysis – PED and GWP (logarithmic scale) (data from PE International 2013)

Furthermore, the acidification potential of different resources is assessed. In Figure 5.6 the results of the assessment are displayed. Overall, a similar "order" of relevance can also be observed for the GWP and AP, which is caused by the fact that most emission contributing to acidification are emitted in the energy supply chain. The AP is dominated by the use of fossil fuels in the production of materials. However, as outlined earlier, many materials are found in sulfide ores where sulfur is linked to different minerals and mining exposes the sulfides to water and air. Even though most modern smelting plants use processes and technologies that reduce sulfur dioxide emissions, the potentially higher relevance of metals produced from sulfide ores in the context of acidification, even if not significant, should be acknowledged (UNEP 2013).[37] Furthermore, *ytterbium* is associated with a comparably higher acidification potential. A possible cause for this could be the fact that *rare earths* are treated with acids to separate the different metals and this separation process is somewhat more difficult for *ytterbium* as it is of lower concentration (Gupta and Krishnamurthy 1992).

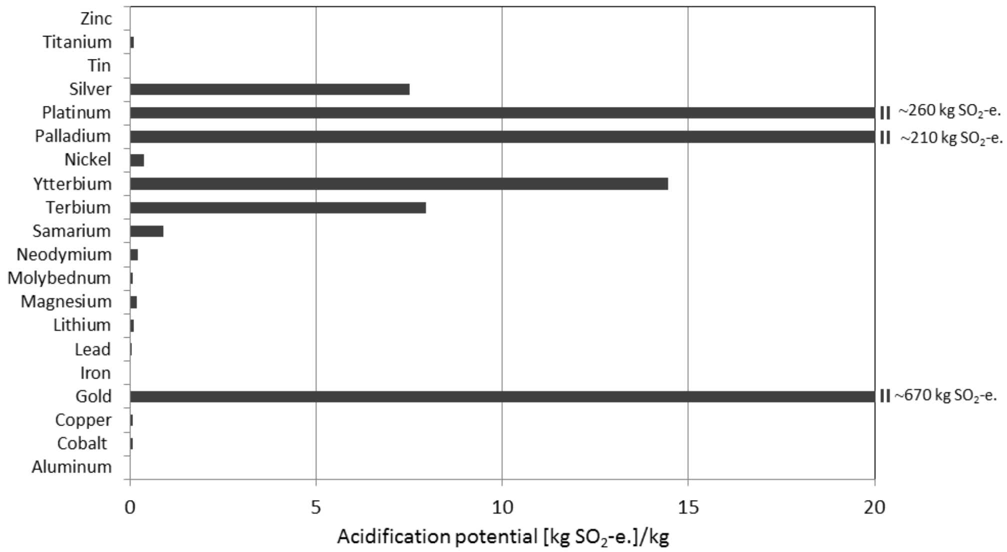

Figure 5.6: LCIA results – Acidification potential (AP) (according to CML-IA). Horizontal axis ends at 20kg SO_2-e.

As a third impact category the potential contribution of the different metals to ecotoxicity is evaluated. The results of the ecotoxicity assessment differ significantly from the previously assessed impact categories (see Figure 5.7). Currently *gold* is associated with the highest AP and GWP, but other materials dominate the results of the ecotoxicity assessment. However, the results of the ecotoxicity assessment have to be interpreted with caution. Firstly, characterization factors for the assessment of ecotoxicity of metal production are associated with a high degree of uncertainty and need to be interpreted in the context of existing shortcomings. Many substances are not yet accounted for in USEtox and only the effects on freshwater are assessed (Rosenbaum et al. 2008; USEtox 2013). Furthermore, characterization factors of metals as such are available in USEtox, but considered as "interim" and should be interpreted with care since they are associated with a high degree of uncertainty. Secondly, the results of the ecotoxicity assessment depend highly on the database used. Characterization

[37] *Copper* and *nickel* for example are comparably more relevant (according to the ranking in the addressed material portfolio) when assessing the AP than for assessing the GWP (see Appendix IV).

results based on ecoinvent data are comparability higher. This is due to the fact, that within the ecoinvent database the long term emission to freshwater are quantified (Frischknecht 2003). These emissions have the highest share on the overall emissions contributing to ecotoxicity and significantly influence the results. Thus the ecoinvent datasets for *molybdenum*, *lithium*, *neodymium* and *cobalt* have significantly higher contributions to the ecotoxicity potential compared to the other categories.

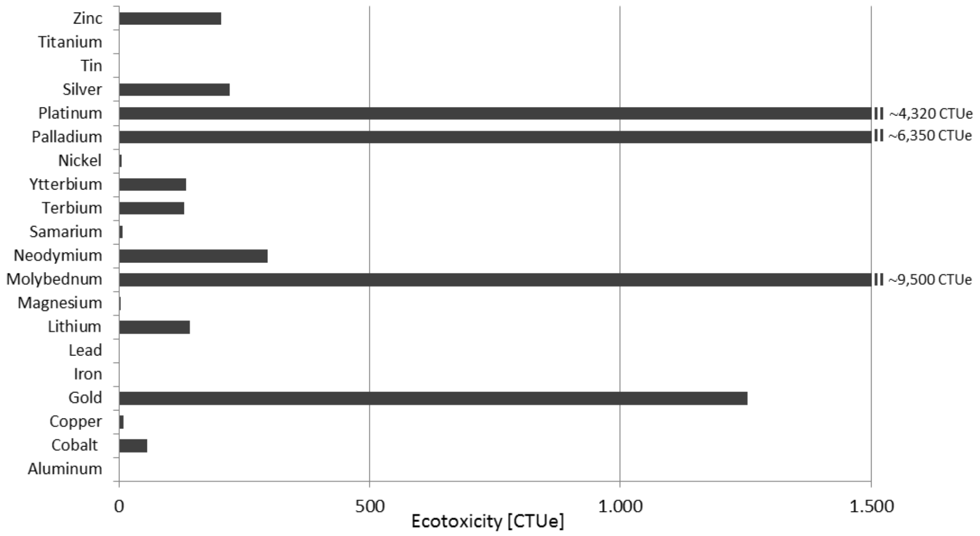

Figure 5.7: LCIA results – Ecotoxicity potential [CTUe] (according to USEtox 2013). Horizontal axis ends at 1500 CTUe.

In Figure 5.8 the results of the ecotoxicity assessment are displayed, but excluding the four materials retrieved from the ecoinvent database.

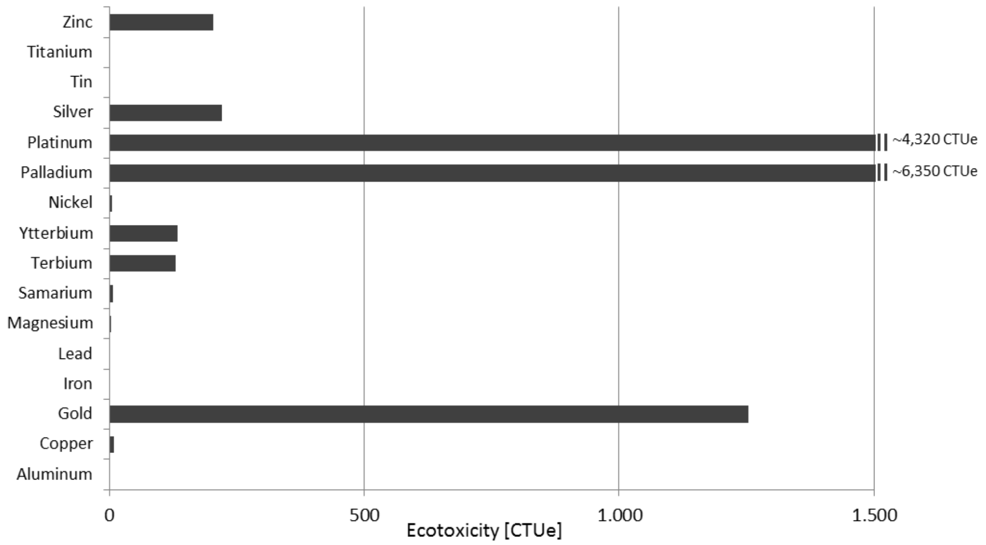

Figure 5.8: LCIA results – Ecotoxicity potential [CTUe], excluding Co, Li, Mo, and Nd (according to USEtox 2013). Horizontal axis ends at 1500 CTUe.

Now a similar distribution of results can be observed as for the GWP and AP, however with relevant differences (e.g., *zinc*). However, to cover a more comprehensive set of materials for the later evaluation in comparison with the other supply risks, for the time being all materials are included in the assessment. However, the underlying inconsistencies have to be kept in mind for the interpretation of the risk scores and decision making.[38]

In a next step, and for developing the environmental risk scores, the characterization results are evaluated based on the distance-to-target method introduced in Chapter 2 (in relation to "1kg" of material). In this study, across all three impact categories, *iron* is associated with the lowest overall impacts. As iron is commonly perceived of being of comparatively low environmental relevance, iron is chosen as a threshold value in this study (see, e.g., Nuss et al. 2014; UNEP 2013). In Figure 5.9 the category indicator results including this "weighting"-step are presented for the different environmental criteria considered in this study. For the presentation of the results, a logarithmic scale is chosen, due to better comparability. As pointed out earlier in this study, the distance-to-target results are a dimensionless quantity determined by the ratio of the characterization results to the threshold material iron.

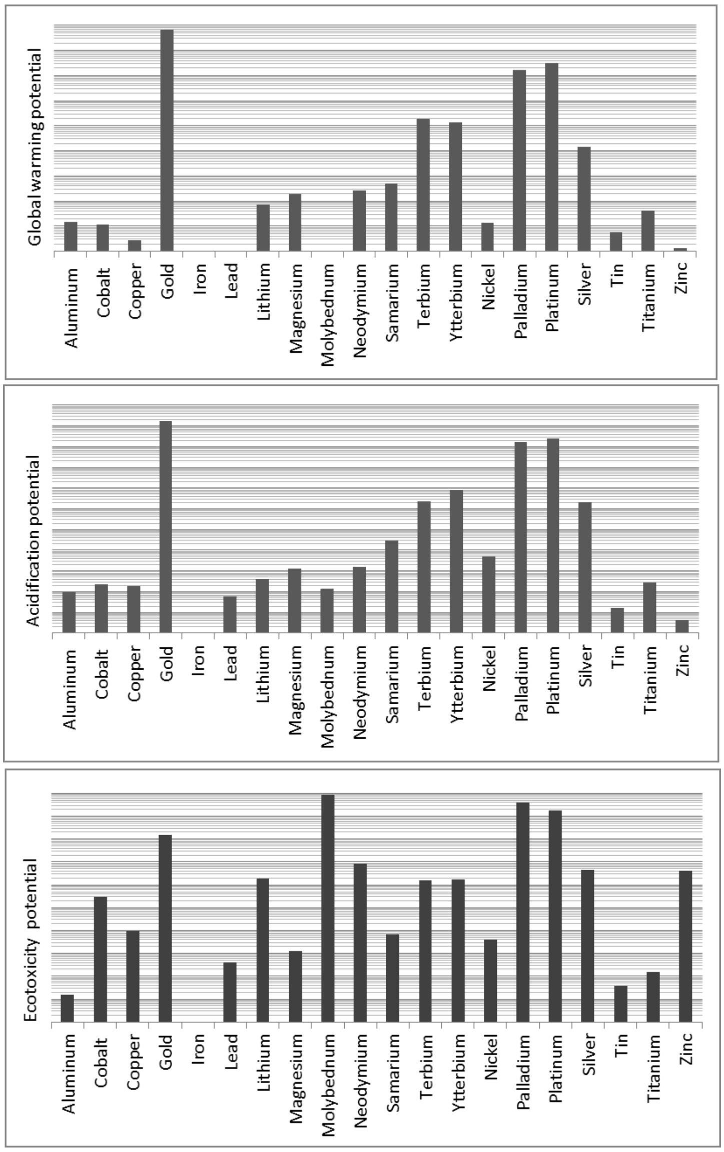

Figure 5.9: Category indicator results (including weighting on basis of the distance-to-target)

[38]In Appendix V an overview of the ecotoxicity potential for some materials based on the different LCI data is provided.

In a final step the category indicator results are aggregated to the single environmental risk indicator (EnSP). Based on the $EnSP_{global}$ presented in Figure 5.10, the metals can be ranked according to their respective environmental risk of supply. Resources delivering the highest $EnSP_{global}$ are associated with the highest environmental risk. The results are also presented using also a logarithmic scale to uncover the risk associated with the different metals. However, the actual scale of the results has to be kept in mind as it indicates the magnitude of risk. As already apparent from the previous figure, *gold*, *palladium* and *platinum* are associated with the highest environmental risks. *Aluminum*, *iron*, *lead*, *lithium*, *tin* and *titanium* seem to be rather uncritical in the comparison. Depending on the impact categories chosen and the assessed material portfolio, other metals could be identified to bear the highest risk.

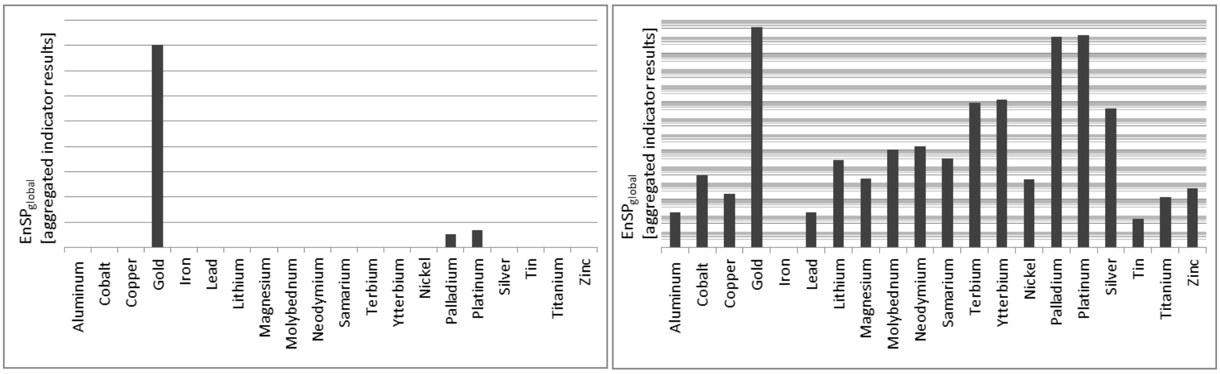

Figure 5.10: $EnSP_{global}$ – normal scale (left) **vs. logarithmic scale** (right)

The assessment of environmental impacts potentially affecting resource provision can be essential to prevent constraints within the supply chain and help to identify “hotspots” and risks associated with industrial resource use. The EnSP method complements existing approaches for the assessment of resource provision capability towards sustainable development. In this dissertation, only the impacts of primary resource supply are assessed. Future assessments should include secondary resource supply into the evaluation. The environmental constraints and consequently the environmental supply risks associated with secondary material are assumed to be lower as generally less energy is required (see, e.g., Graedel et al. 2014).

The results have to be seen in the context of several shortcomings. The results of the EnSP are determined by the choice of environmental impact categories considered and the choice of impact assessment method used. For determining the environmental dimension of resource provision capability, only three environmental impacts have been considered so far and the assessment of additional environmental impacts could lead to different results and a changing overall EnSP. Furthermore, system boundaries of available data sets might differ, the age of data is often very high, and assumptions are not always transparent. Furthermore, the assessment of the GWP and the AP are currently based on characterization factors published by the Institute of Environmental Sciences in Leiden (CML) (CML 2013). However, other impact assessment methods are available that could affect the results. One of the newer impact assessment methods available is the ReCiPe-method (Goedkoop et al. 2008), which can be seen as an advancement of the CML-method. In Appendix IV results of both assessment methods are compared to highlight the sensitivity of the assessment to the choices made. However, despite these shortcomings, the evaluation is based on current best practices and used data is the basis for every environmental product evaluation as of today. The current approach has to be seen as a first step towards a more holistic consideration of environmental issues that constrain resource supply.

In the next section additional discussion is provided with regard to the interpretation and evaluation of the results.

5.4 Additional considerations

Beyond the shortcoming already addressed in the previous sections (limited availability of characterization methods, inconsistency of databases) additional aspects are of relevance for the interpretation of results.

The underlying objective of assessing the environmental risk associated with different materials lies in the assumption that high impacts can potentially constrain resource supply. Environmental damages associated with different materials are thus used as a basis to evaluate the respective supply risk. For this purpose, this work relies on existing databases and uses existing LCI data. For evaluating the environmental impacts of different metals, the ecological burden of mining needs to be distributed among the coupled products. In current databases it is most common to allocate the outputs from metal production according to an economic relationship (relative price) (UNEP 2013). Thus, the environmental impacts associated with the different materials are to some extent influenced by their economic value and not the 'real' situation of metal production is represented with existing data. In Figure 5.11 the correlation of LCIA-results and respective prices of the different materials is shown. The influence of the economic value on the environmental impacts has to be considered for the interpretation of results and for making conclusions with regard to actual environmental risks and, for example, the probability of immediate constraints.

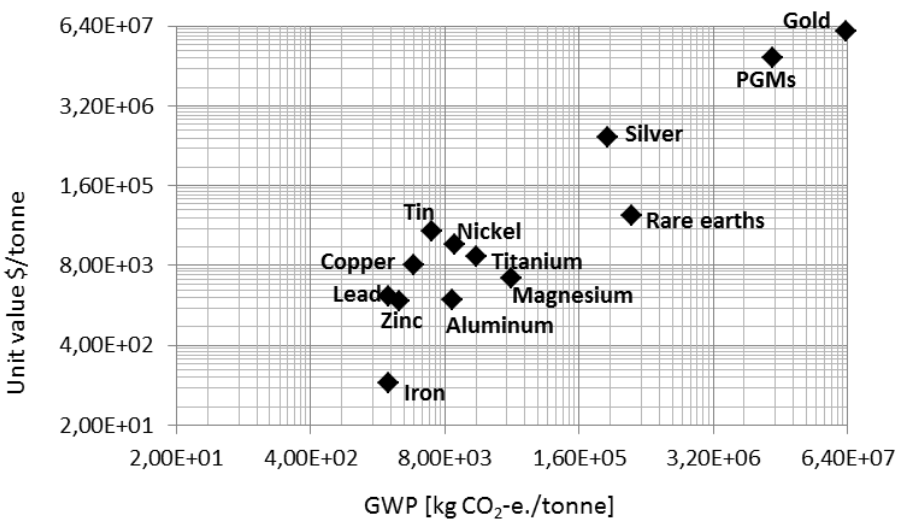

Figure 5.11: Correlation of unit value [\$] and GWP [kg CO_2-e.] (based on data by PE International 2013; USGS 2014a)

In this study, global risk scores were to be identified. The process data in existing databases are often indicated to be of global nature. However, these datasets do not necessarily reflect the real shares of production as published by the USGS (USGS 2013a). The global *gold* mix as published by PE International (2013) is a mix of data from South Africa, Ghana, Peru and Australia. These countries do actually not display the real global production mix and have only a share of 38% of the global production of *gold*. It is inexplicit to what extent these datasets are representative for the determination of the average global EnSP. For a meaningful management of environmental risks to supply and for improving supply chains the actual production processes and environmental impacts in the different countries would need to be evaluated. However, such data is not available and can hardly be obtained. The data in existing databases represents the current best approximation of the overall global situation.

6 SOCIAL CONSTRAINTS TO RESOURCE SUPPLY – THE SOCIAL RESOURCE SCARCITY POTENTIAL

Abstract

To conduct business in a socially responsible manner, social aspects of resource provision need to be considered. In the context of increasing public awareness, potential negative social impacts in the supply chain of a material can indirectly constrain the availability of resources also at levels where people are not directly affected.

Social impacts may concern infringement of labor rights, violation of human rights or aggravation of living conditions. Such aspects can influence the public acceptance of products and can jeopardize corporate social responsibility goals. This can have effects on the availability of certain materials at a product level. Relevant social aspects need to be identified and social risks associated with materials need to be assessed and integrated in decision making.

So far, the consideration of social aspects has not been integrated into decision making practice. In this chapter, relevant social aspects potentially constraining resource supply are identified and social risks associated with different materials are assessed. A model is developed to include social risks into the assessment of resource provision capability by considering social hotspots along the supply chain of materials. By means of the social resource scarcity potential (SSP) the social supply risks associated with different material are analyzed.

Materials produced to a large share in countries with poor social performance and high risks for social impacts are associated with high social supply risks. Rare earths and cobalt, produced for the most parts in China and Congo, are associated with the highest SSP based on material portfolio assessed in this work.

The SSP enables a comparison of the social supply risks associated with different materials and enables the integration of social aspects into decision making practice.

6.1 Social constraints to resource supply: an overview

Social aspects represent the third dimension of sustainability and need to be considered for a holistic assessment of resource provision capability. Without addressing social aspects, the assessment of sustainability would not be complete (Azapagic 2004). In this first section the assessment of social constraints is outlined in the context of resource provision capability and relevant social aspects are identified.[39]

An estimated 45 million people are involved in mining activities, representing over 1% of the world's workforces and many other people are directly or indirectly employed in the minerals supply chain (Azapagic 2004; IIED and WBCSD 2002). For any mining project there will be

[39]Social aspects represent issues that are considered to be threatening social well-being (UNEP/ SETAC 2009). In this dissertation, the risk of social aspects to occur (e.g., child labor) are assessed.

social impacts (Hustrulid and Kuchta 2006). Per definition of the United Nations Environment Programme (UNEP/ SETAC 2009), “social impacts are consequences of positive or negative pressure” on, for example, wellbeing of workers. In this dissertation, focus is on the risk for negative social impacts in terms of potential bottlenecks to supply. Sustainable resource management involves choosing materials under consideration of potential negative social aspects along the supply chain which should obviously be avoided.

Negative social consequence of mining range from violations of human rights to effects on local communities and poor working conditions (GHGm 2008). These aspects can *indirectly* constrain the supply of resources, due to low stakeholder acceptance or limited compliance with corporate goals and governmental regulations (political guidance). An overview of this interrelation is given in Figure 6.1. Mining activities and circumstances are more open than ever to public perceptions. Social responsibility can be an indicator of judging companies (Liu et al. 2012). Companies cannot afford to look at resource supply in isolation from the social system which they are a part of (Brown 2002).

Figure 6.1: Causes for social constraints on resource supply (based on information from Benoît-Norris et al. 2012; European Commission 2008; Weterings et al. 2013)

For the assessment of social constraints, this dissertation identifies relevant social aspects following the guide for social life cycle assessment (SLCA) published by the UNEP/SETAC Life Cycle Initiative (UNEP/ SETAC 2009). However, SLCA is less established than LCA (Jørgensen 2012; Jørgensen et al. 2013) and limited data with regard to the different impact categories is available. Databases such as for LCA do not yet exist and data collection proves difficult as a focus on companies engaged in the supply chain and their conduct is needed (Dreyer et al. 2010). Even though SLCA can provide guidance for assessing social impacts of products, an approach for the determination of potential constraints associated with resource provision in the context of sustainable development is still missing. For the evaluation of the social dimension of resource provision capability, social aspects need to be prioritized. In this dissertation, social risks are evaluated that are relevant for the mining and minerals sector and perceived to potentially constrain resource provision capability (see, e.g., Azapagic 2004; European Commission 2008). Similar to the evaluation of the environmental risks associated with the provision of resources (see Chapter 5), the basis for social constraints to resource supply is the concern over social conditions or the social performance of a product. Consequently, only social aspects with high public interest will actually function as a constraint to resource supply. Thus, the assessment from a social perspective does not include a comprehensive assessment of all potential social impacts associated with mining activities. Instead, only aspects that are of low societal acceptance and that could potentially affect access to certain resources are addressed.

Currently, the only available database for conducting SLCA is the social hotspot database (SHDB). The SHDB is a meta-analysis of the best country and sector-specific social data available. SHDB data are characterized to the average level of risk for a social aspect to occur instead of a real impact and can be used to identify social hotspots[40] (Benoît-Norris et al. 2012; Martínez-Blanco et al. 2014; Norris et al. 2014). Thus, the identification of relevant social aspects in this dissertation is limited to data available in the SHDB (2014).[41]

The aspects addressed in this dissertation were identified based on following criteria:

- Relevance in the context of public awareness
- Avoidance of double-counting with criteria addressed in the economic analysis (e.g. corruption)
- Data availability

In the context of identifying relevant social constraints to resource supply, the following social aspects are chosen that have been associated with high media attention and are assumed to be of high public interest (see, e.g., Kannan 2014; Mirovalev and Kramer 2013; Spiegel Online 2013; Teevs 2010):

- Child labor
- Forced labor
- High conflict zones

Aspects like child labor or forced labor have generated negative publicity in the past and they are assumed to potentially constrain resource provision (e.g., Norwegian government funds are withdrawing money from companies associated with child labor, Apple aims at prohibiting child labor in their entire supply chain (Apple Inc. 2013; Spiegel Online 2013)). Child labor has been a topic of intensive debate and abolition of child labor is defined as a prerequisite for sustainable development (European Commission 2008). Furthermore, several policy initiatives exist on a national and international level that aim at banning the trade in “conflict” minerals and to increase sustainability in the extractive industries (Weterings et al. 2013). The identified issues display some of the key sustainability issues for the mining and minerals sector as identified by Azapagic (2004) and according to the Global Reporting Initiative (GRI) (2013). Other social aspects are of relevance for the mining sector, including

[40] Social hotspots are unit processes located in a region where a situation occurs that may be considered a problem or a risk in relation to a social aspect of interest (UNEP/ SETAC 2013). Social hotspots can generally also refer to situations that may be considered as an opportunity. However, regarding the scope of this dissertation only aspects that could constrain resource availability are considered.

[41] In the SHDB different categories (i.e., labor rights, human rights) are analyzed by a range of specific indicators for multiple social aspects (i.e., child labor, forced labor). Either a single indicator or several indicator are used to characterize the risk of particular social aspects (Benoît-Norris et al. 2013).

for example aspects related to local communities such as delocalization and migration, violations of indigenous right or secure living conditions. However, as no data is available on these topics in the SHDB they are excluded from further evaluation as of the time being. In Table 6.1 the aspects taken up in this work for the assessment of social risks are described in more detail (as per definition of Benoît-Norris et al. 2012; Benoît-Norris et al. 2013; Norris et al. 2014).

Table 6.1: Overview of social aspects (based on SHDB 2014)

Aspect	Description
Child labor	Risk of Child labor in a country (differentiated by sector). Child labor refers to work for children under the age of 18 that is mentally, physically, socially and/or morally dangerous or harmful or interferes with their schooling.[1]
Forced labor	Risk of forced labor in a country. Forced or compulsory labor is any work or service that is exacted from any person under the menace of any penalty, and for which that person has not offered himself or herself voluntarily.[2]
High conflict zones	Risks for high conflict are quantified. Conflicts are defined as the clashing of interests over national values between at least two parties that are determined to pursue their interests. Conflicts can include societal and interstate warfare. This aspect needs to be considered to consider if the organizations act in conflict zones.[3]

[1]Benoît-Norris et al. (2013) [2]ILO (2014) [3]according to Heidelberg Institute for International Conflict Research (2011), UNEP/SETAC (2013)

Social performance is associated with the conduct of companies in the supply chain rather than with the material as such. However, many minerals are traded internationally. Thus, detailed information on the supply chain and involved companies is often difficult to attain and to trace back. As information on the actual social performance can generally not be obtained, the average social risk is determined in this study based on the global share of production for each material. However, when the models developed in this work are implemented, the determination of risks should preferably be as detailed as possible under consideration and management of specific supply chains and involved actors.

In the next section the methodology for determining social risks is introduced. The proposed model will allow for an evaluation of resource provision capability from a social angle and can be integrated into material choices on a product level.

6.2 The social resource scarcity potential: causal relation and methodology

In this section, the development of the methodology for identifying relevant social hotspots associated with the provision of different resources is outlined.

The social dimension of resource provision capability relates to the social performance along the supply chain of materials in the context of the potential supply risks. Supply risks can occur at a level where people are not directly affected due to limited stakeholder acceptance, non-compliance with corporate goals, and so on. The identification of supply risks might differ if assessed from a company or societal perspective. For assessing resource availability social hotspots or bottlenecks[42] need to be identified that threaten social wellbeing and affect the provision of resources in the context of sustainable development. This cause-effect relation is displayed in more detail in Figure 6.2.

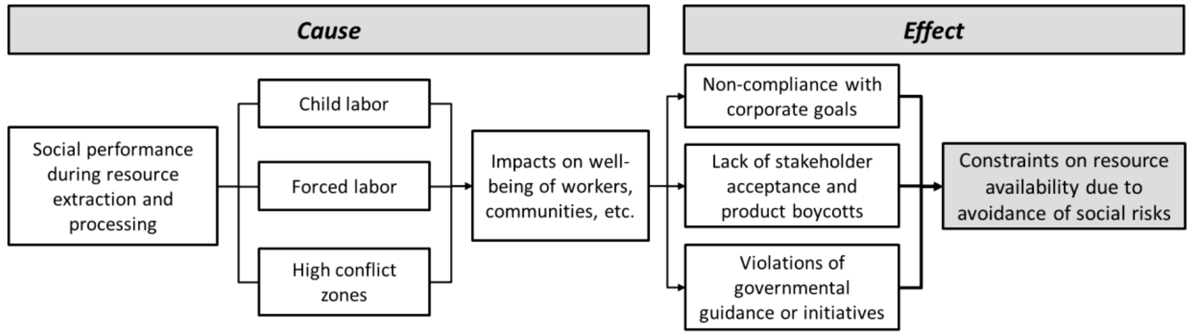

Figure 6.2: Cause-effect-relation – Social performance and risks of resource provision

Social impacts are hardly determined by physical flows, but mainly by the way a company conducts towards different stakeholders (Dreyer et al. 2010; Jørgensen et al. 2008). In an era of complex supply chains identification of social aspects and potential social risks of materials is not easy. However, social risks or hotspots in the supply chain of resources need to be considered in order to make decisions that support sustainable development. Each of the supply chain stages of a material can be at geographic locations where social impacts might occur (UNEP/ SETAC 2009). Similar to the environmental constraints (see Chapter 5), social constraints can occur at any stage of the supply chain and can lead to immediate constraints (e.g., regulations or limits associated with the exploitation and extraction of resources) or retrospective constraints (e.g., child labor in a specific country can affect acceptance of resources in later stages of the supply chain). In line with the earlier definition of the scope of this study, the use-phase is excluded from the assessment and only supply risks associated with the resource provision level are described, focusing on the mining stage.

Following the assessment described in previous chapters, the identified aspects (child labor, forced labor, high conflict zones) are evaluated with regard to their potential to constrain resource supply. For identifying the social risks associated with resource provision capability, the contribution to the risk needs to be quantified and included in the characterization model. An assessment based on SLCA is challenging, as databases comparable to those in environmental LCA are lacking (Martínez-Blanco et al. 2014). Limited data availability and assumptions create high levels of uncertainty. Average risk values as published in the SHDB represent the best available data for the assessment of social risks associated with a country and the respective sector and are thus used as a basis for the evaluations in this dissertation.[43] The average risk values as published in the SHDB need to be evaluated with regard to their potential to constrain resource supply. The different aspects need to be measured

[42]According to UNEP/SETAC (2009) social hotspots are identified as processes „located in a region where a situation occurs that may be considered as a problem, a risk or an opportunity, in function of a social theme of interest.“ The term bottleneck can be used as a synonym for negative hotspots.

[43]In line with the scope of this dissertation, positive impacts are not assessed in the SHDB (Benoît-Norris et al. 2013).

quantitatively according to their contribution to a social risk associated with resource provision capability. Thus, in line with previous chapters, the risk value is placed in relation to a target that facilitates an interpretation and evaluation of risk. Hence, in line with the definition in Chapter 2, a ‘distance-to-target’ method is used to include a threshold or “scale of risk” into the modeling. It needs to be acknowledged that social impacts are a function of political and economic situation, ethics, psychology, culture, etc. Thus, the definition of negative social impacts and societal acceptance can differ significantly in different countries and depend on policies, perceived relevance for sustainable development, and so on.

In practice, the definition of threshold values needs to be oriented on national, societal or corporate goals and can vary for the different social aspects. In this dissertation the threshold value is set to “0.01”. This value represents the lowest possible risk identified in the SHDB. In the context of uncovering all potential social risks associated with material production and under consideration of the goal to avoid all social impacts this value can thus be seen as the best estimate.

The resulting impact factors (I_{SSP}) are a function of the average risk values (R_{avg}) and the threshold above which potential constraints to supply can be expected. These factors are calculated for each resource (i) and each impact category (j) (see Eq. 12).[44] The advantage of using data from the SHDB is that all data are available in a consistent scale. Thus, the data does not need to be adjusted but can be directly used as a basis for the distance to target evaluation.

$$I_{SSPi,j} = \mathrm{Max}\left\{\left(\frac{R_{avg\,i,j}}{\mathrm{threshold}_{i,j}}\right)^2; 1\right\} \qquad \text{(Eq.12)}$$

The social impact factors are calculated for each material and give an indication about the magnitude of the risk. The “distance-to-target” approach allows a spread of the results, enabling the identification of hotspots by linking the impact factors to the material inventor of products. In this regard, only a comparison of different resources can provide a meaningful estimation of associated supply risks and a basis for decision-making (see also previous chapters).

For the evaluation of the overall relevance of different materials and for the comparison with other resource assessment approaches the calculated impact factors for the social aspects can be combined to a single *social resource scarcity potential* (SSP) for each resource, enabling a ranking of social risk for easy implementation on a product-level. For calculation of the SSP impact factors are aggregated using multiplication to reinforce risks (Eq. 13) (see also discussion in previous chapters).

$$SSP_i = \prod_j \left(I_{SSPi,j}\right) \qquad \text{(Eq.13)}$$

[44]Generally, to avoid compensation during further aggregation of impact factors, no values below “1” are permitted in the assessment. However, in this conservative approach, using the lowest risk value, no results below “1” will occur.

The aim of the methodology developed in this section is the identification of the overall social risk associated with different materials in the context of an evaluation on a product level. The assessment delivers relevant information for identifying social hotspots in the supply chain and for making material choices that consider potential social constraints to resource provision capability.

In the following section, this methodology is applied to a portfolio of 17 metals and results are presented.

6.3 Results

In this section, 17 metals are assessed with regard to the social risk associated with their provision in the context of sustainable development. Production steps with potentially high social impacts occur mostly along the early stages of the supply chain of a material. Thus, in this dissertation, only the social risks associated with mining are evaluated. Different sectors are addressed in the SHDB based on the classification of the Global Trade Analysis Project (GTAP), referring to the primary or basis production stages (extraction, mining, production, casting, etc.) of metals and minerals as well as crude oil (Benoît-Norris et al. 2013; GTAP 2013; SHDB 2014). [45] *Copper*, *zinc*, and *lead*, are carrier metals, that are linked to several co-element that have no, or limited own production infrastructure (Reuter et al. 2005). For those elements (e.g., *cobalt*, *cadmium*) it makes sense to apply the same sector data as a basis for further evaluation. Furthermore, according to SHDB data only minor differences occur between the average risk values for the different sectors of metal production.

The global average risk values for the identified social aspects (child labor, forced labor, child labor) and for each metal are presented in Figure 6.3 (based on an inventory of 1kg of each metal). The average country risks are weighted by the share of production in different countries to calculate average risk scores for each material.

[45]The method can also be applied for other resources such as fossil fuels. However, the choice of sectorial data needs to be adapted accordingly.

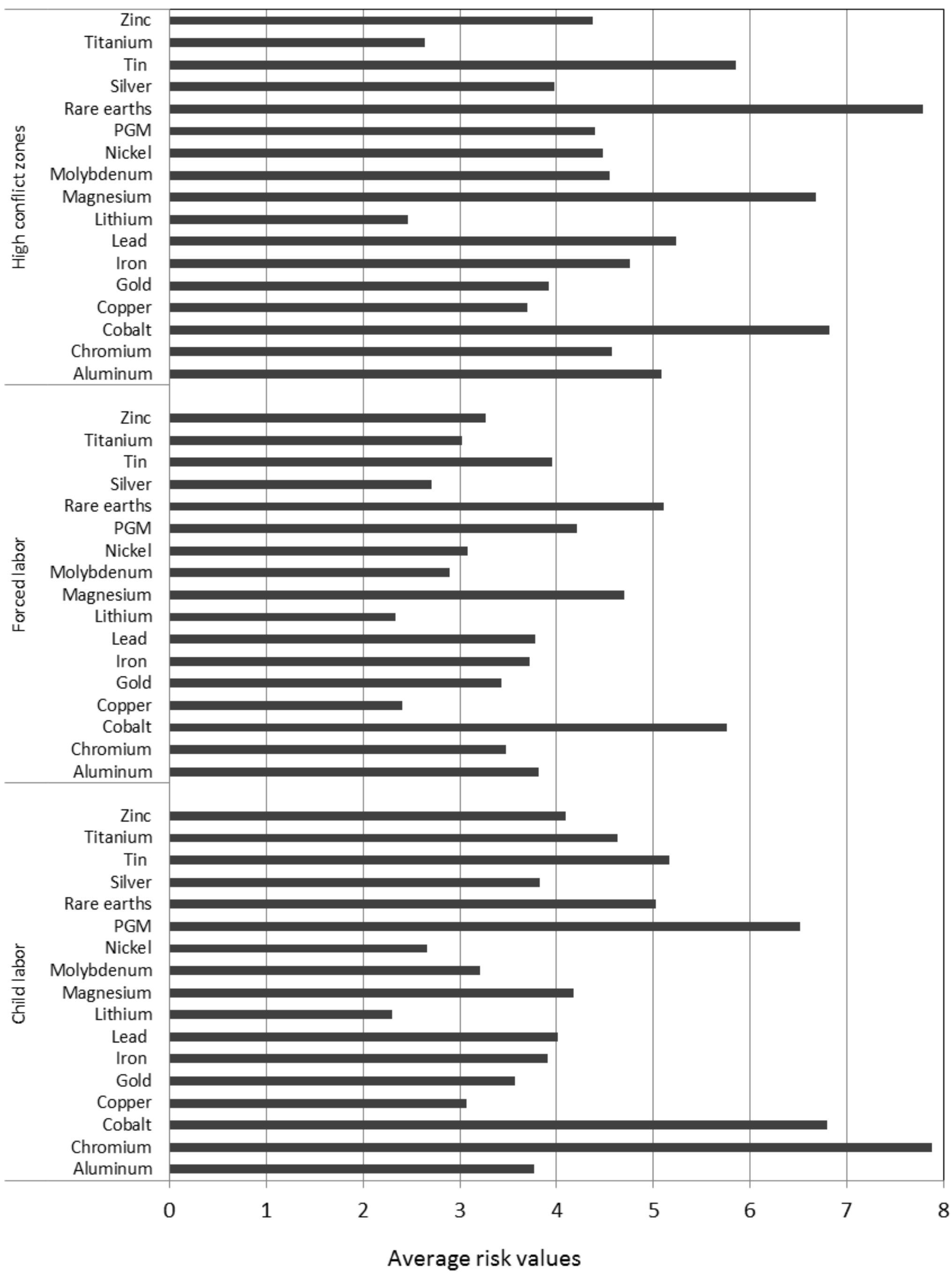

Figure 6.3: Average risk values for different materials (based on data published in the SHDB 2014)

The analysis shows that materials which are produced to a large share in Asia have a comparably high risk for child labor. Africa has the greatest incidence of children at work (according to ILO (2002) 41% of children in the continent are at work). This is reflected in the analysis in Figure 6.3. *Chromium*, *cobalt* or *PGM* for example, which are produced to a large share in South Africa, are associated with a high risk for child labor. On the contrary, *lithium*, which is mainly produced in South America and Australia, is associated with lower social risks across all three aspects.

As the thresholds were defined equal for all three social aspects, the comparative evaluation based of the impact factors (I_{SSP}) determined by the distance-to-target approach will deliver the same conclusions as displayed in Figure 6.3. However, if the thresholds (targets) are varied for the different social aspects different results might be obtained when using the proposed methodology. In Figure 6.4 a compact overview of the percentage contribution to the overall supply risk is shown. The relevance of the three social aspects for the evaluated materials is highlighted. While child labor plays an important role for materials mostly produced in Africa and some countries in South America, materials produced to high shares in Asia are associated with a high risk for conflicts. Forced labor is of high concern for materials produced in for example Russia or India.

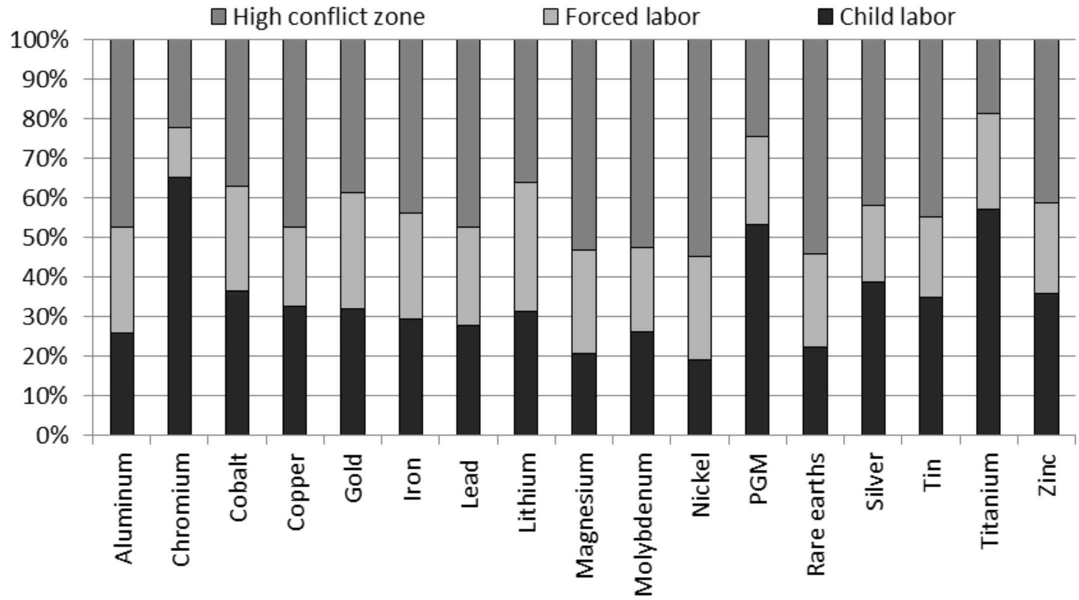

Figure 6.4: Relevance of addressed social aspects [%]

As a next step, the impact factors displaying the average risk for child labor, forced labor and high conflict zones are aggregated to the *social resource scarcity potential* (SSP). The SSP_{global} is calculated for a holistic determination of risks associated with the different materials from a global perspective. In Figure 6.5 the results for the comparative assessment of the different materials are presented.

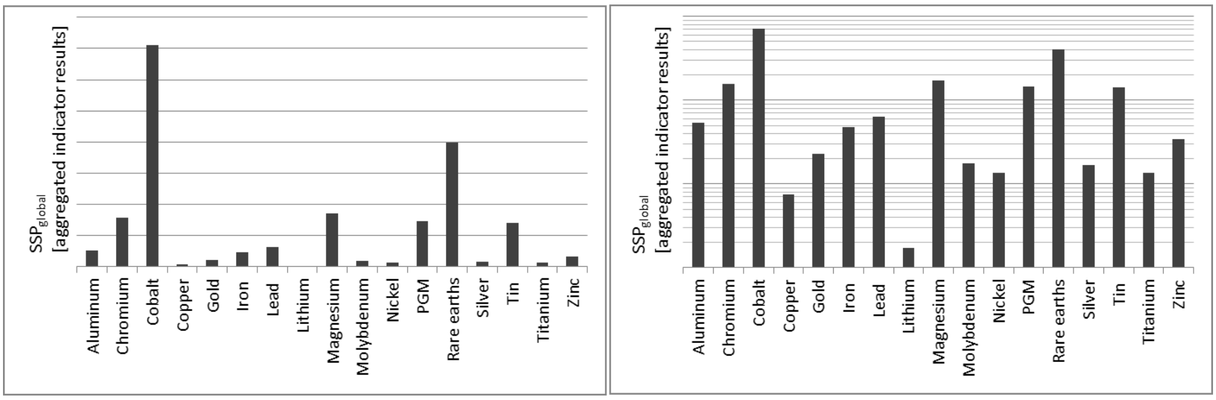

Figure 6.5: SSP_{global} – Normal scale (left) **and logarithmic scale** (right)

Even though the spread of the results is not as significant as for the economic or environmental assessment of potential resource scarcity, the social risk associated with, for example, *cobalt*, and *rare earths* is several magnitudes higher than for other materials. Consequently, these metals have a high potential for social constraints, and material choices need to be made under consideration of these social constraints in the supply chain. Contrary, *lithium* for example is associated with very low social risk as a large share of production takes place in Chile and Australia, both of which are associated with low country risks for social impacts. However, the assessment of social constraints to resource provision capability has to be seen in the context of the current limitations with regard to available data and impact pathways. Thus, the results should be interpreted really as what they are: an identification of potential hotspots associated with the provision of different materials. The results do not aim to quantify actual social impacts of the addressed materials but highlight the potential social supply risk and deliver decision support for avoidance and management of these risks.

In the next section, additional considerations are discussed, highlighting the limits of available data.

6.4 Additional considerations

Social impacts are difficult to capture (Dreyer et al. 2010). Social LCA is thus still striving to attain maturity. The assessment of social aspects for an evaluation of the social performance of different materials needs to be seen in the context of its potential to uncover risks (hotspots) rather than describing actual social impacts (see Jørgensen 2012; Jørgensen et al. 2010b). The SHDB provides a solution to enable the initial assessment of social hotspots (Benoît Norris 2014). However, site specific data collection would be needed for a realistic representation, which is beyond the means for the assessment of average global risks. Furthermore, the data basis is incomplete (which is caused by limited data availability on social aspects). So far, countries that do not report any data on certain aspects are not considered in the calculation of the average risk (Benoît-Norris et al. 2013). Furthermore, data completeness is not very high for the addressed countries and sectors: For child labor the data completeness for country data lies at 72% and for sectors only by 26%. For forced labor, no sector data is available and the average risk values are based on data on a country level. Data completeness here is only around 80%. The analysis of social aspects in the supply chain of different resources strives for the identification of social risks or hotspots. For a more realistic representation of social risks, resource provision needs to be managed by engaging with supplier, and by identifying how certain companies in the supply chain conduct. Company specific data would be needed to realistically determine potential social impacts associated with different materials.

As already outlined in the previous section, the results of the social resource scarcity potential have a lower spread than the other methods (ESP, EnSP). On one hand this is due to the average risk data retrieved from the SHDB weighted by the share of the production across different countries. While the effects of the environmental and economic assessment are often global and are based on indicators or environmental impacts, the social dimension of resource provision capability is already based on data that depict a risk rather than an actual situation. On the other hand, the low spread of data is caused by the distribution of production activities associated with the different materials. In Figure 6.6 an overview of the share of production across all countries involved in production is provided.

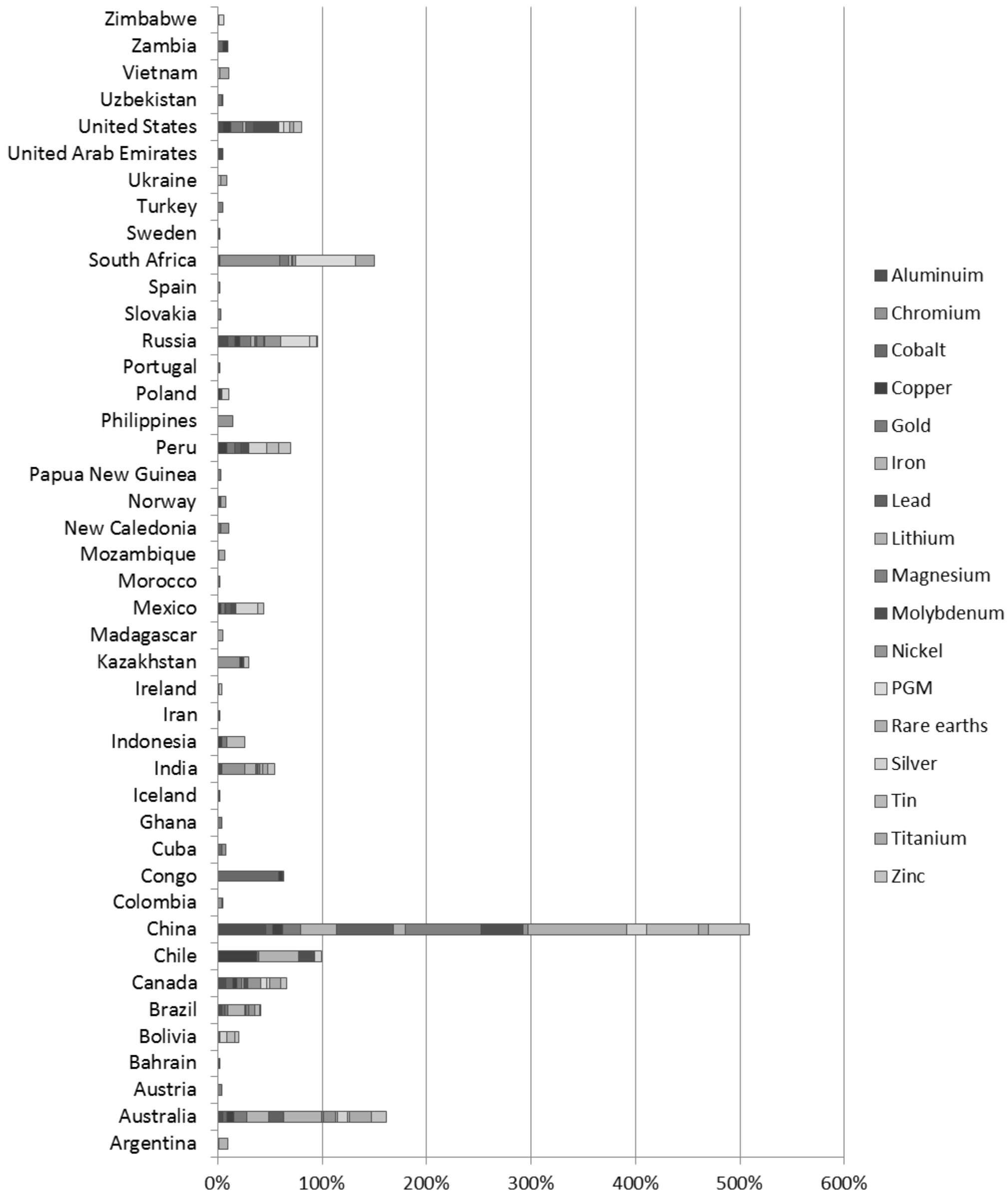

Figure 6.6: Percentage of mine production in different countries (based on data by USGS 2014a)

Few countries dominate the overall production. China has the highest share of mine production across all materials and produces more than 30% of the total volume of the materials assessed in this study. As China has shares above 50% for the production of many metals, the similarity of the results of the social risk assessment is not a big surprise.[46] In Figure 6.7 an overview of China's share in metal extraction for the assessed material portfolio is displayed, highlighting the conclusions drawn based on Figure 6.6.

[46]Similar results are also obtained for the assessment of governance stability and socio-economic stability in Chapter 4 as the share of production in different countries is the basis for the assessment, too.

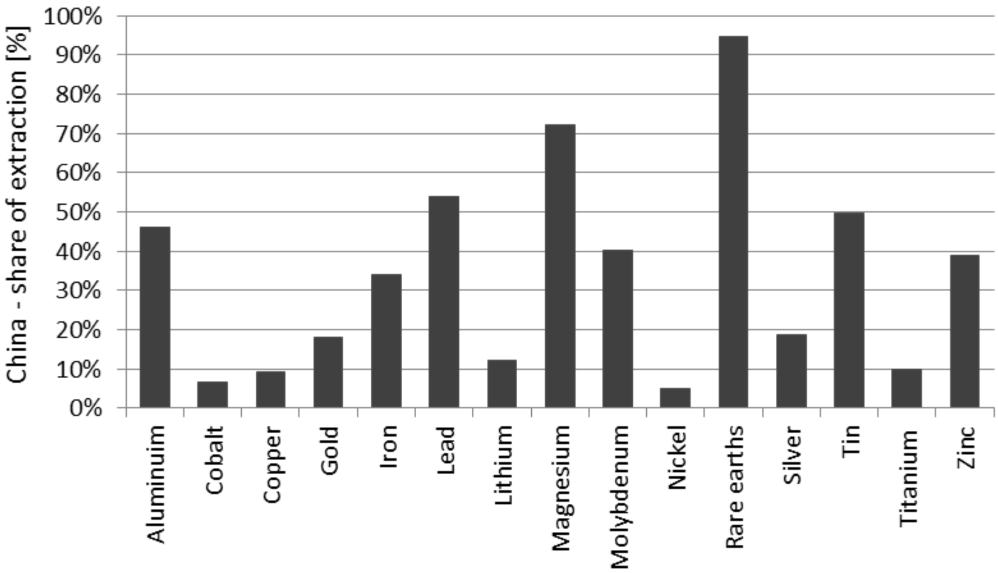

Figure 6.7: China – Share of metal extraction [%] (based on data published by the USGS 2013a)

The SSP provides an overview of the average social risk associated with different materials. Despite the shortcoming of the underlying database, the results can be seen as a current best estimate and can serve as a basis for decision making and for avoiding materials associated with high social risks. The analysis of country-specific circumstances is relevant for managing resource supply and for making material choices in the context of sustainable development.

7 COMPREHENSIVE ANALYSIS: RESULTS AND DISCUSSION

In the previous four chapters, a new parameterization for the depletion of abiotic resource was introduced, acknowledging the functional value of resource. Furthermore, the supply risk of resources was evaluated taking into account economic, environmental and social constraints. Addressing only one of these dimensions of resource provision capability does not provide all the information needed as a basis for sound and informed material choices. A comprehensive assessment is needed and the different dimensions need to be addressed simultaneously. This chapter provides a comparative overview of the results of physical, economic, environmental and social assessment of resource availability. In Figure 7.1 the approach in this work and the different dimensions of resource provision capability are displayed. Even though a comprehensive evaluation of resource provision capability encompasses both dimensions, no single-indicator result combining physical and effective scarcity is proposed.

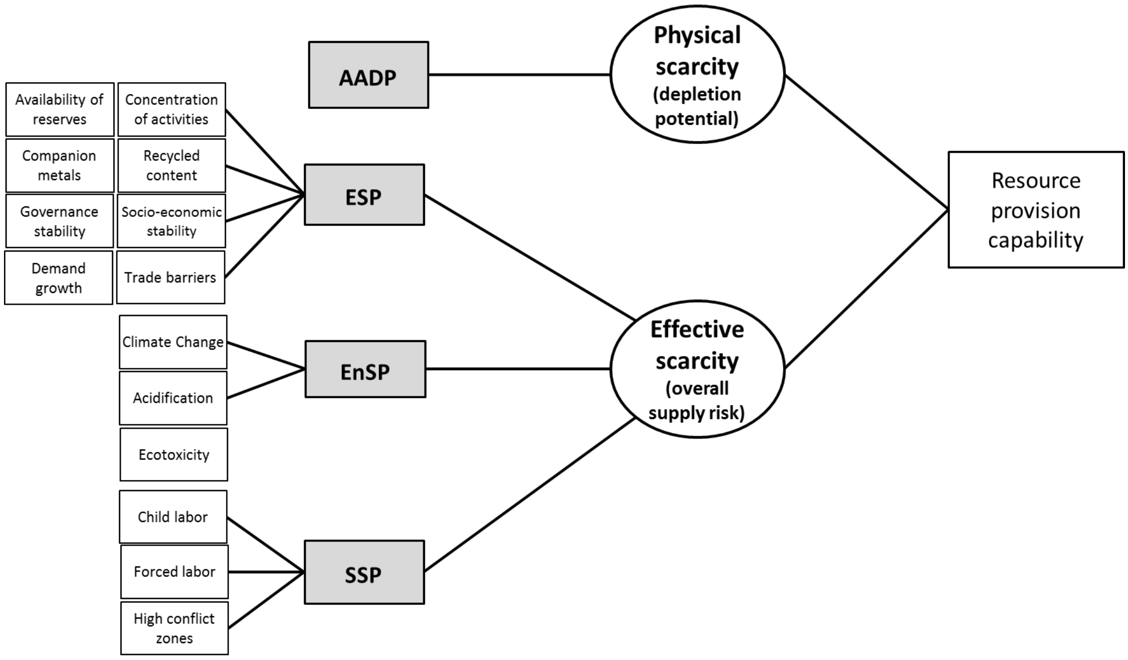

Figure 7.1: Dimensions of resource provision capability

An aggregation of these two types of scarcity to an overall resource provision capability is possible in theory, however not recommended in this dissertation as an aggregated indicator score is hard to interpret and delivers no decision support for mitigating risks. Supply risk and depletion are two markedly different issues and their individual relevance depends on value choices and the emphasis of current or future generations.[47] The temporal reference as well as the cause-effect-network are inherently different. Evaluation of effective and physical scarcity is based on different ways of looking at resource scarcity and the implications for decision making are fundamentally different depending on the perspective taken. While preventing

[47]Following for example an individualist perspective, applying a short term focus, only effective scarcity would count and physical scarcity would be evaluated as of low relevance. From an egalitarian perspective a precautionary approach is followed, focusing on long-term effects. From this perspective, physical scarcity would gain relevance.

depletion requires a reduction in the use of a specific resource, for avoiding or minimizing supply risks the supply chain needs to be assessed and the risks are independent from the amount of the material used. Supply risk requires measures in the short term and depletion refers to long-term goals and influences future resource availability.

Effective scarcity comprises potential economic, environmental and social constraints. For determining the overall global supply risk (SR) for each material (i) these different dimensions are aggregated (see Eq. 15). No ranking of the different dimensions is anticipated in this work and all dimensions of resource availability are assessed under equal consideration and relevance.[48]

$$SR_i = ESP_i \times EnSP_i \times SSP_i \qquad \text{(Eq.14)}$$

For the aggregation of the different dimensions of potential resource scarcity, multiplication is used again to reinforce the overall supply risk. As the risk scores vary in their absolute values (due to the number and choice of indicators and the underlying databases), a summation would lead to misleading results, not properly displaying the individual dimensions of resource scarcity (as low risk scores would not affect the overall supply risk) (see also Chapter 2.3). A normalization of the results to one material, for example copper, would change the absolute results, but not the ratio of the supply risks between the different materials. As normalization would complicate the interpretation of results, no normalization is applied. In Figure 7.2 the results of the proposed methodologies for the assessment of physical and effective scarcity are presented (per kg of material). The magnitude of the AADP and SR results is high. As any exceeding of the threshold implies a potential risk the results are presented using a logarithmic scale to uncover the risks and depletion potential of all assessed metals (without a logarithmic scale only *PGM* would appear for the SR and only *gold* for the AADP). Based on the AADP model, focusing on potential resource depletion, *rhenium*, *PGM*, and *beryllium* are associated with the highest concerns. The overall supply risk is clearly dominated by *PGM*, *rare earths* and *gold*.

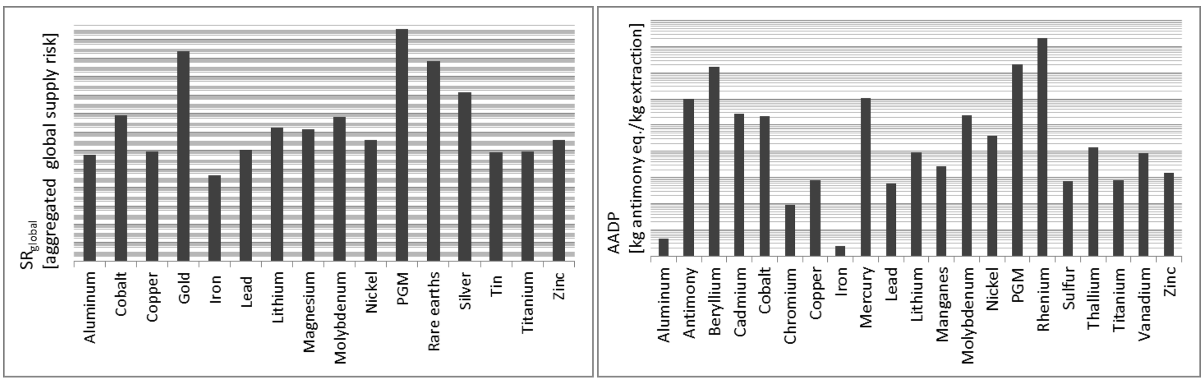

Figure 7.2: Effective and physical scarcity – Overview of results[49]

In Figure 7.3 the different materials are compared with regard to their supply risk and depletion potential and the differences in the ranking of materials are highlighted. Hereby, the ratios between the different materials are evaluated. For example, from a supply risk

[48]A different weighting of the dimensions of supply risk is possible.
[49]Average values are used for *rare earths*. *Platinum* is displayed representative for *PGM*.

perspective, *Cobalt* is associated with overall supply risks almost twice as high as molybdenum. Contrary, *molybdenum* is associated with a slightly higher potential for depletion (1.1 times higher). Furthermore, the overall range of the supply risk and depletion potential is highlighted by showing the ratio of the material associated with the highest supply risk and depletion potential to the material with the lowest relevance in the addressed portfolio. By means of the ratio the individual relevance of the materials can be highlighted. Based on the displayed ratios comparative statements can be made supporting decision making. The representation of the ratio is limited to the materials defined in both dimensions of resource scarcity. Based on this representation, a statement can be made with regard to the relative relevance of individual materials in the context of the addressed material portfolio. *PGM* are the materials with the highest overall supply risk and also with the highest potential for depletion. Similarly, *aluminum* and *iron* are associated with the lowest values for both dimensions.

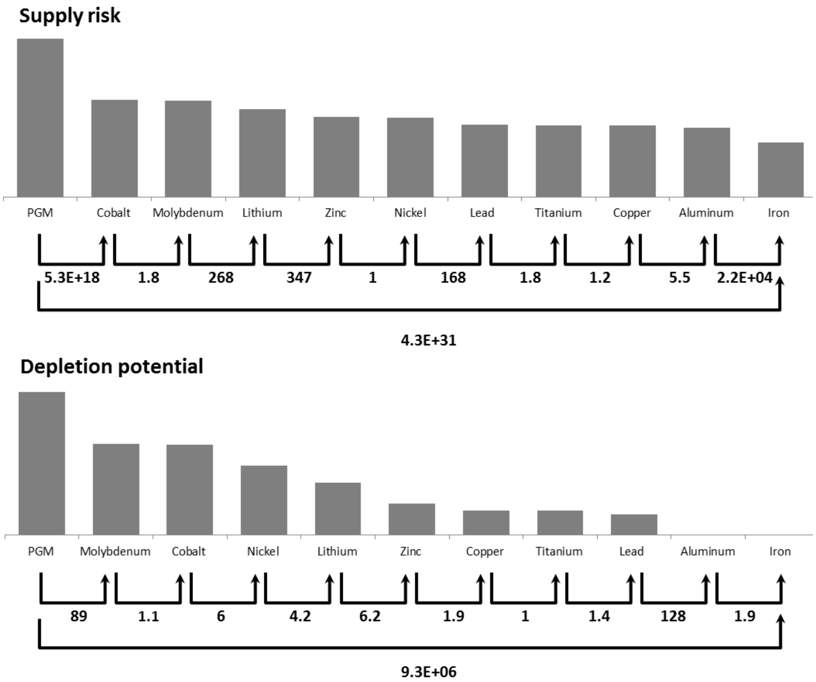

Figure 7.3: Ratio between materials – Supply risk and depletion potential (logarithmic scale)

In a next step, to highlight the additional value of the methods developed in this dissertation, a comparison with conventional resource assessment practice by means of the ADP is provided. For the evaluation of the different dimensions of resource availability the absolute comparison of the results is not meaningful, as the underlying reference values and methods differ. For identifying the depletion or risk of materials the comparative assessment is of relevance. The interpretation of the depletion potential outside of a comparative context is not possible. Even though reductions of the depletion potential of individual materials could be assessed, no statement could be made with regard to the relevance of the material in a global context. The evaluation of supply risk can be evaluated with regard to the exceedance of defined targets and the respective distance-to a target. But again, only a comparative evaluation provides incentives for decision making material choices.

Firstly, the new parameterization of resource depletion by means of the AADP model in comparison to the ADP model is revisited (the differences of the results have already been discussed in Chapter 3). By adapting the resource figures used as a basis and relating to the ultimately extractable resource rather than the concentration in the earth's crust and by including anthropogenic stock into the assessment significantly different results are obtained. In Figure 7.4 the results are presented, enabling a comparative overview (ordered by size).

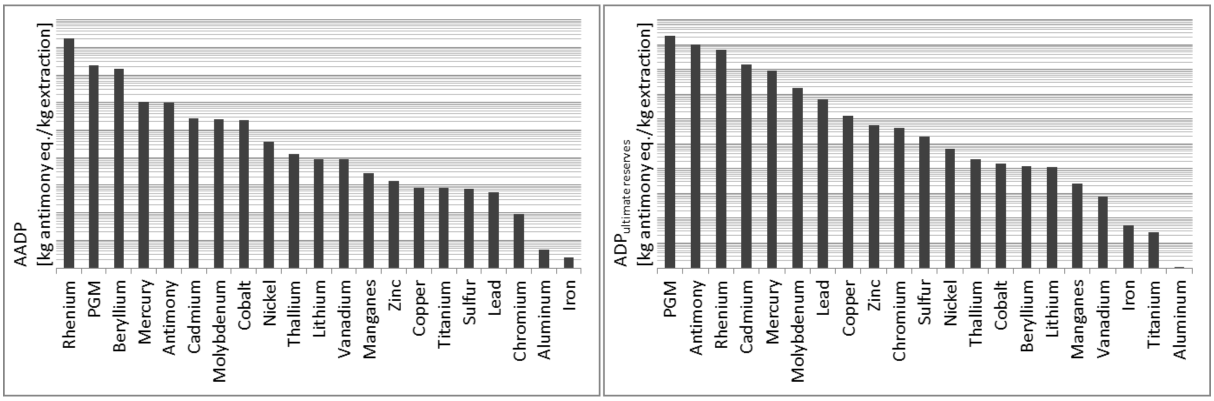

Figure 7.4: AADP (left) **vs. ADP** (right) (ADP data based on van Oers et al. 2002)

Secondly, to highlight the added value of the methods for assessing supply risk in relation to current resource assessment practice, a comparison of the SR and the ADP is presented in Figure 7.5 (ordered by size of supply risk/depletion potential). The supply risk is a dimensionless quantity while ADP results are a relative measure with the depletion of the element *antimony* as a reference (van Oers et al. 2002). The different methods lead to different conclusions. While *gold* and *PGM* are critical from a supply risk as well as from a geologic perspective, *rare earths* and *magnesium* for example are associated with high supply risks but are so far not identified as of concern based on ADP models. The use of *rear earths* may be constrained, but the overall stock has only a low potential for depletion based on these results.

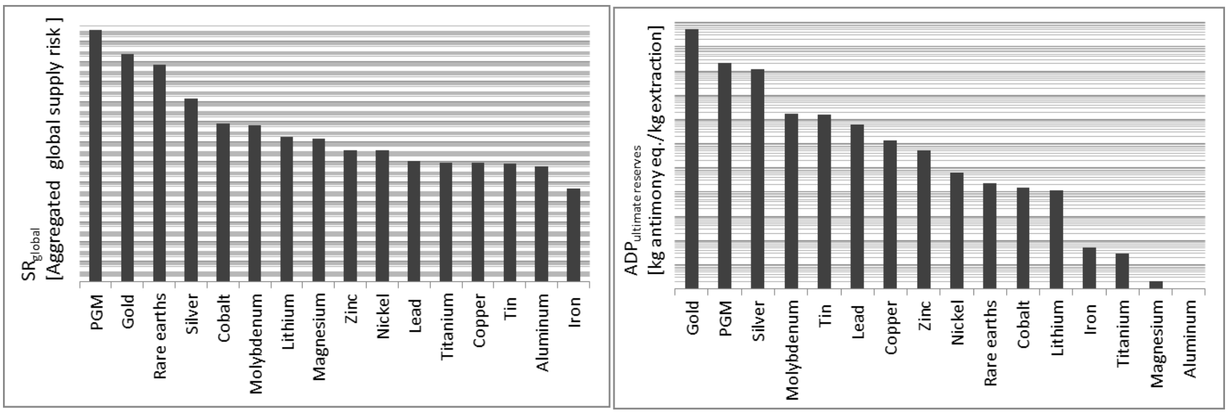

Figure 7.5: SR (left) **vs. ADP** (right) (ADP data based on van Oers et al. 2002)

The results of the models developed in this work can be used as a basis for decision making and to focus the attention of companies on certain materials or to highlight relevant issues associated with the availability of resources. Both dimensions need to be thoroughly studied and resources with low impacts on resource depletion and low supply risk should be chosen. The developed models provide a more comprehensive picture of resource provision capability and can complement and replace existing models for addressing resource use and availability. However, for informed decisions and actions the different dimensions of supply risks need to be evaluated individually. The aggregation of the results can provide an indication of the respective relevance of different materials, but can obscure the nature of the underlying challenge. The aggregated supply risks deliver no information on individual dimensions and specific risks or bottlenecks. It needs to be evaluated whether the supply risks are of economic, environmental or social nature to take appropriate measures for mitigating or avoiding these risks. For managing resources and to compare and weight the different dimension of supply risk against each other, a detailed assessment of the different resource scarcity potentials is needed. In Figure 7.6 an overview of the different dimensions of resource scarcity and a ranking of the materials is presented. Again, to uncover the individual contribution, a logarithmic scale is used for the comparison.

The risks differ significantly for the different dimensions of supply risk. Resources that are of no concern from an economic perspective can be associated with high social or environmental supply risks (see, e.g., *gold* or *tin*). While from an environmental perspective *gold* is most critical, *rare earths* and *PGM* are associated with the overall highest economic supply risk. From a social perspective, resources that are produced in countries with a high risk of social impacts are associated with the highest supply risk (e.g., *cobalt* and *rare earths*, produced mainly in Africa and China). However, the results need to be interpreted in the context of the shortcoming outlined in the respective chapters. No absolute comparison of the results of the different dimensions can be made (see same discussion earlier in this chapter). The absolute values are influenced by value choices (e.g., number and choice of indicators considered, definition of the threshold) and the inherent characteristics of the underlying indictors. The ESP for example consists of the aggregation of eight different indicators, while the environmental and social resource scarcity potential each consist only of three different indicators. However, for a comparative assessment of different materials linked to specific materials relative values are meaningful and sufficient.

Other than for the environmental and economic dimension of risk, risk scores of the SSP model are significantly lower (see Figure 7.6). Thus, when linking the risk scores to the material inventories, the relevance of the inventory is much higher and identified risks might be mitigated by high quantities of specific materials. This originates in the underlying data used for determining the social supply risk and due to the combined use of qualitative and quantitative data which are aggregated into an average risk of one country. Furthermore, this is caused by the high share of production in few countries and consequently similar average risk values for the different materials (see Chapter 6). The low spread of the resulting risk scores and the overall lower values lead to a lower reinforcement of risk than for the other categories.

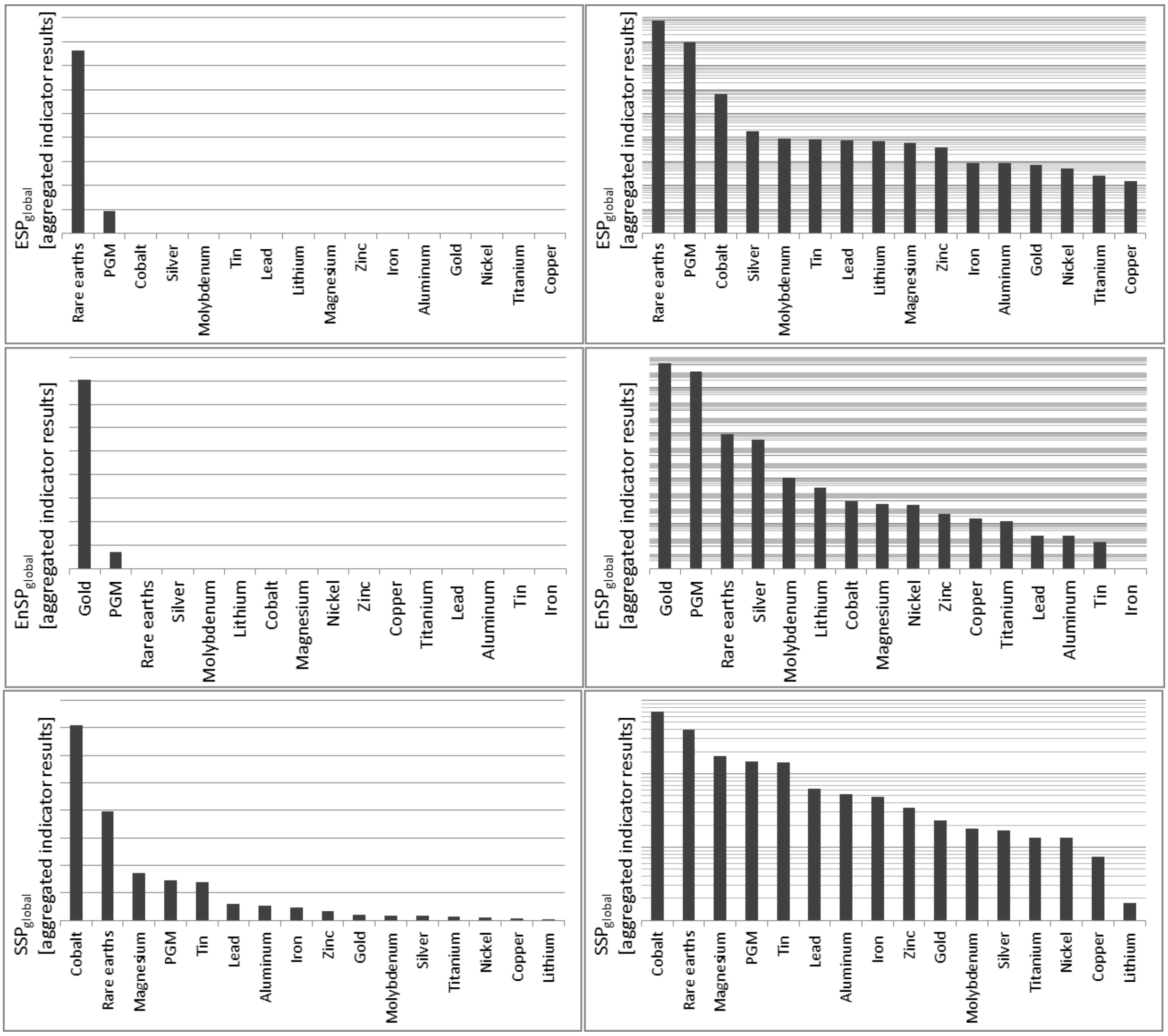

Figure 7.6: Overview of different supply risk dimensions, normal (left) **and logarithmic scale** (right)

In Figure 7.7 the relevance of the different materials in the context of the different dimensions of supply risk is highlighted by displaying the ratio between the different metals. The figure highlights again the overall spread of the results. This is important for the interpretation of the supply risks. Even though every value above “1”, per definition of this work, indicates a supply risk, the magnitude of the risk of individual materials is highlighted by means of displaying the ratios. Of special interest is the identification of materials that stand out and are associated with significant risk in one of the dimensions. The ratios allow for a statement of the relative relevance of the materials such as *rare earths* are associated with an eight time higher ESP than *PGM*. The ratio can be used to highlight the results and make comparative statements. The actual impacts of high versus low ratios can however not be determined. Only the higher probability that constraints to resource supply might occur for certain materials is outlined.

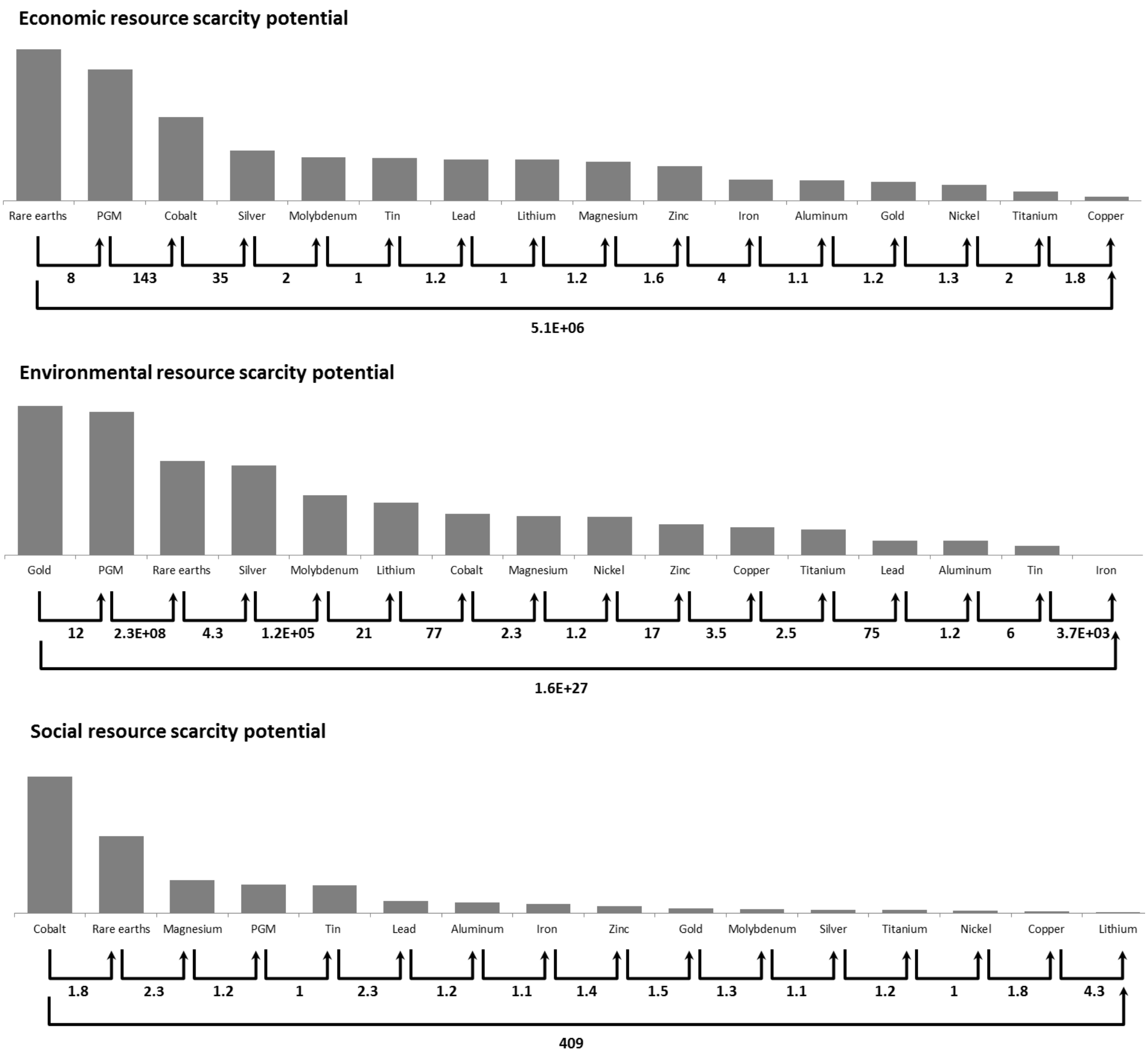

Figure 7.7: Ratio between materials – Evaluation of the dimensions of supply risk (logarithmic scale)

The ratio of the material associated with the highest risk to the material associated with the lowest risk shows the overall spread of risk scores within the different dimensions. For the economic resource scarcity potential, the high risk of the top three materials is obvious. *Rare earths*, *PGM*, and *cobalt* are associated with significantly higher economic risks than the other materials. The ratio between the different materials for the assessment of the environmental dimension of resource provision capability is more diverse. Here, too, *gold* and *PGM* are associated with significantly higher risk than other materials. However, the ratios between the materials are in general more significant (e.g., *PGM* have an ESP over 200 million times bigger than *rare earths*). The significantly lower spread of risk scores for the SSP can be observed also with regard to the displayed ratios.

For reducing supply risks, companies should first tackle materials associated with high risks. The logarithmic scale used in previous figures "disguises" the fact, that the supply risks within the different dimensions are dominated by only few materials. Due to the high spread of results for the economic and environmental resource scarcity potential, few materials dominate the respective results. However, any distance to the threshold describes a risk and needs to be taken into account for decision making and management of materials and for improving social and environmental standards in the supply chain. Even though ra*re earths, PGM, gold* or *cobalt* are associated with high supply risks in the different dimensions, other materials are also associated with significant supply risks and cannot be disregarded. In Figure 7.8 the high ratios of results by displaying the contribution of the individual materials to the three dimensions of supply risk are highlighted. The results of the different dimensions are dominated by few materials (see previous figures). Thus, in Figure 7.9 and Figure 7.10 the dominating materials are excluded from the overview and the results are displayed again for the different dimensions of supply risks.

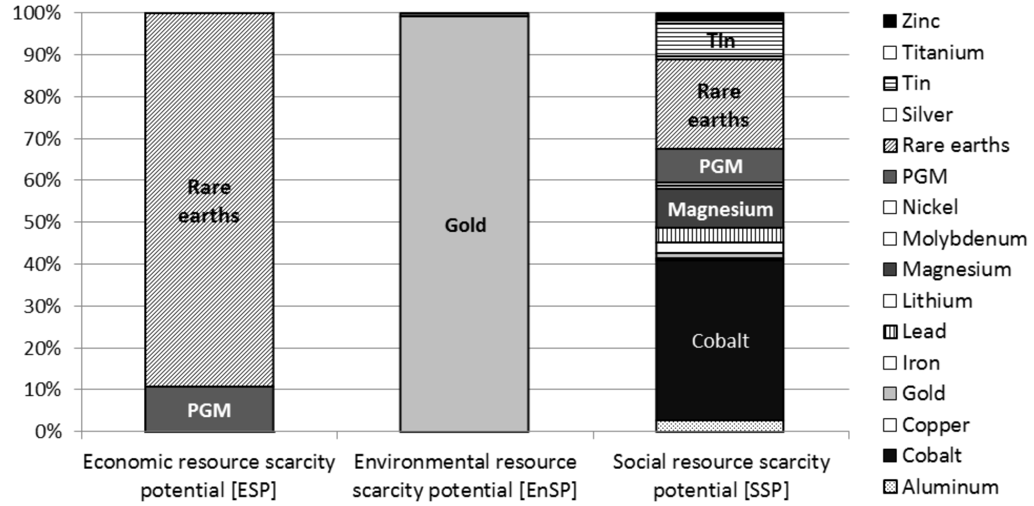

Figure 7.8: Contribution of individual metals to supply risks [%]

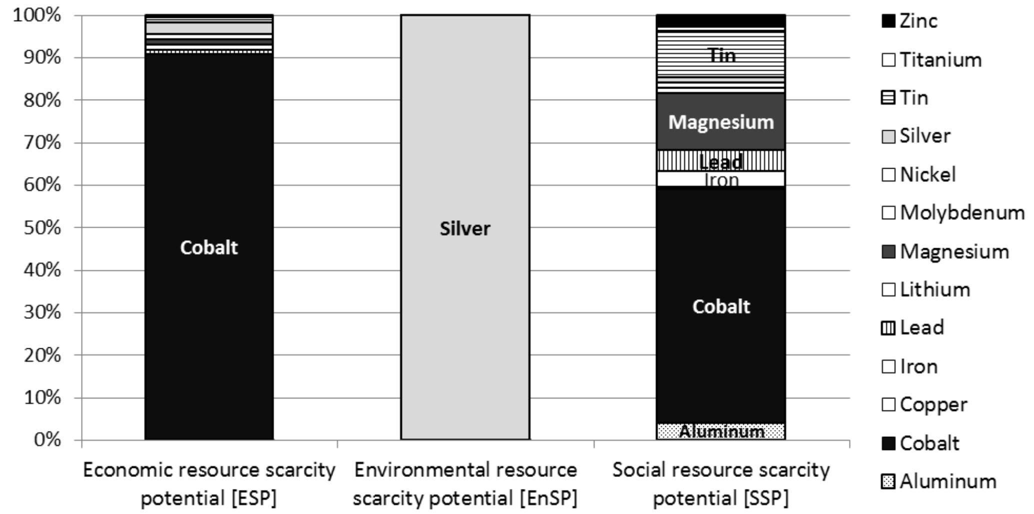

Figure 7.9: Contribution of individual metals to supply risks [%], excluding *gold*, *rare earths*, and *PGM*

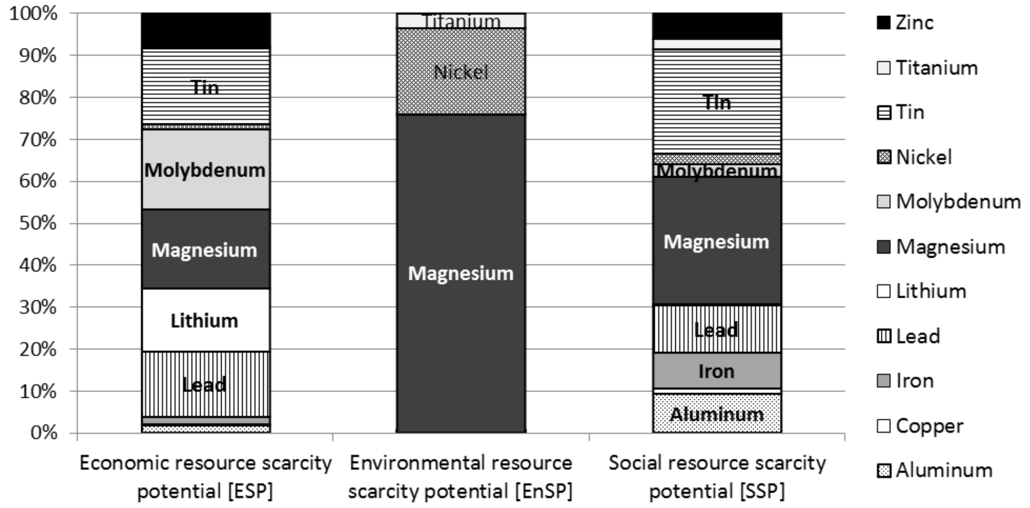

Figure 7.10: Contribution of individual metals to supply risks [%], excluding *gold*, *rare earths*, *PGM, cobalt,* and *silver*

In Figure 7.11 an overview of the different materials in the context of their economic, environmental and social resource scarcity potential is provided (based on the data displayed in Figure 7.6, logarithmic scale). This figure provides a comprehensive overview of the ranking of the different materials across the different dimensions.

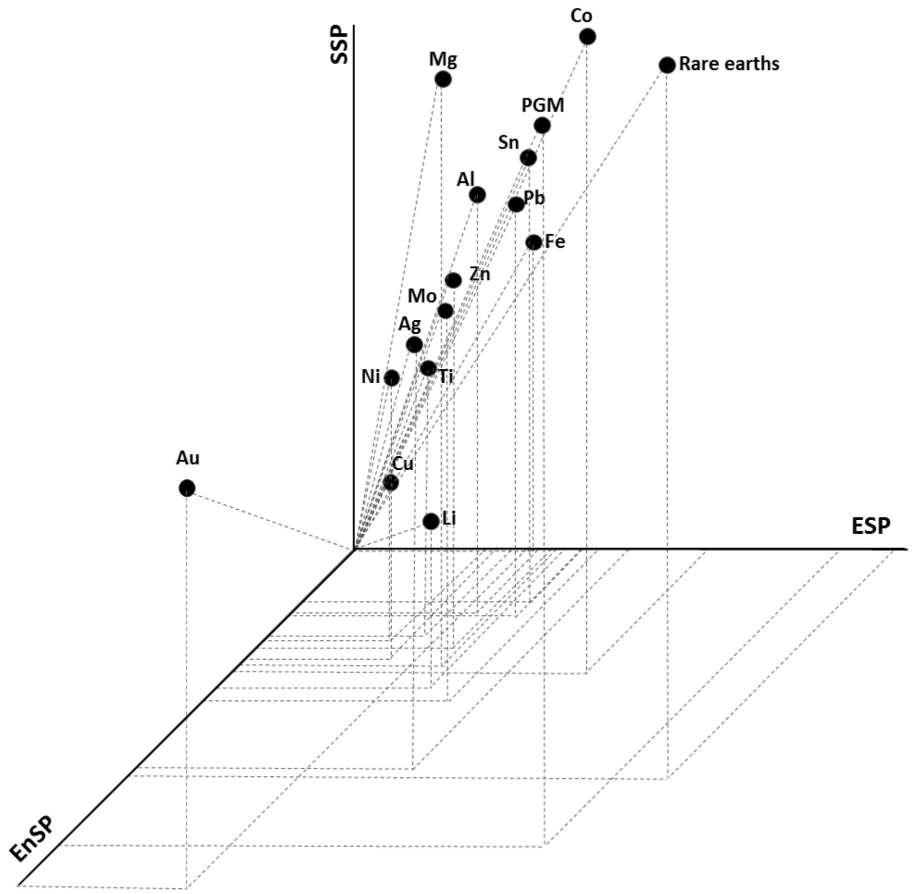

Figure 7.11: Overview – Economic, environmental, and social supply risk (logarithmic scale)

The results of the new parameterization of depletion and the identification of supply risks lead to fundamentally different results than results obtained in current resource availability assessment practice. In Table 7.1 an overview of the five most relevant materials according to the different methods is presented. This representation needs to be seen in the context of the here addressed material portfolio.

Materials that have a low potential for depletion can be associated with high environmental, economic or social risks. *Rare earths* are a good example. While they appear under the "Top 5" materials for all three dimensions of supply risks, they are of no relevance with regard to potential depletion. Furthermore, based on the assessment, *PGM* can be identified as very critical. In all methods, *PGM* are among the "Top 5" materials and can thus be evaluated as of high concern with regard to continued resource provision capability.

Table 7.1 Overview of results

Depletion		**Supply risk**			
ADP	**AADP**	**ESP**	**EnSP**	**SSP**	***ADP***
PGM	Rhenium	Rare earths	Gold	Cobalt	*Gold*
Antimony	PGM	PGM	PGM	Rare earths	*PGM*
Rhenium	Beryllium	Cobalt	Rare earths	Chromium	*Silver*
Cadmium	Mercury	Chromium	Silver	PGM	*Molybdenum*
Mercury	Antimony	Silver	Magnesium	Tin	*Tin*

As different material portfolios are assessed for depletion and supply risks, ADP is represented twice.

To further test the developed methods and to highlight the added value for decision making, a simplified case study is presented, based on data of two different vehicles. The material data is based on a previously published study (see Schneider et al. 2011). Technological changes in the automobile industry and the introduction of electrified vehicles to reduce the emissions during the use phase and the dependency on fossil fuels, promote the use of "new" materials. In this context concerns are raised that new dependencies are created and new risks occur. In Table 7.2 an overview of the simplified material inventory is provided for one electrified (S400 Hybrid) and one conventional vehicle (S350).

Table 7.2: Material inventory – *Mercedes S400 Hybrid and Mercedes S350*

	Mercedes S400 Hybrid (kg)	Mercedes S350 (kg)
Steel	1035	1006
Aluminum	282	260
Copper	34,4	24,2
Nickel	0,95	0
Cobalt	0,17	0
Lithium	0,13	0
Rare earths	0,221	0

In Figure 7.12 the results of the assessment of the material inventory by means of the conventional $ADP_{ultimate\ reserves}$ and the AADP model are presented. In current resource availability assessment, *copper* dominates the results, When using the new parameterization *cobalt* is associated with the highest supply risk, followed by *nickel* and *copper* (*rare earths* are not included in the evaluation of AADP as no characterization factors are available yet).

Rare earths and *lithium* don't seem to play a very important when evaluated based on their potential for depletion, due to the high geologic stocks of *rare earths*[50] compared to the other materials. However, these two materials are considered as the most important elements for the scale up of EVs (see, e.g., Angerer et al. 2009a; Wadia et al. 2011) and continued availability is highly debated. Models for addressing physical availability were not able to reflect these concerns. Here, the developed methods for the assessment of supply risk come into play, addressing and quantifying the causes for these concerns and displaying economic, environmental, and social constraints.

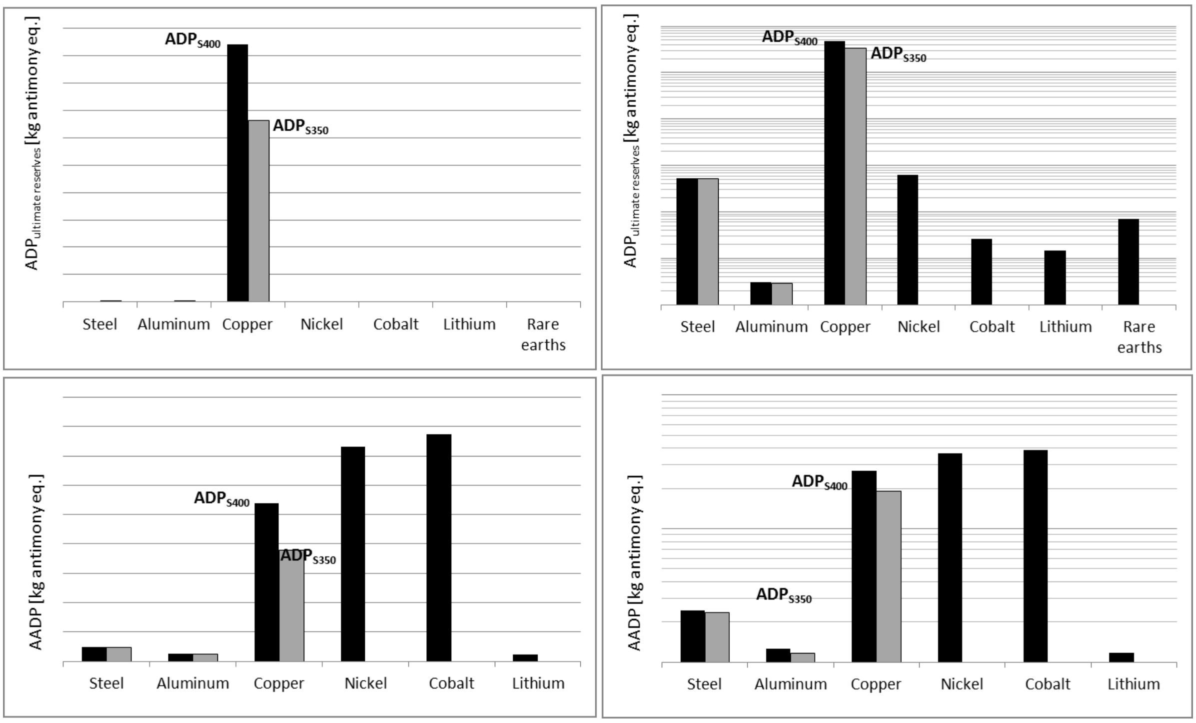

Figure 7.12: Case study results – AADP and ADP$_{\text{ultimate reserves}}$, normal scale (left) **and logarithmic scale** (right) (ADP data based on van Oers et al. 2002)

The evaluation of the material inventory based on the ESP, EnSP, and SSP leads to significantly different results (see Figure 7.13) and provides relevant decision support. *Rare earths* are identified as being associated with the highest economic and environmental supply risk, despite the comparably low quantity that is used The social dimension of supply risk is dominated mainly by the quantity of the materials used, due to the low margin of results (see also previous discussion and additional considerations in Chapter 6).

The models enable companies to make more informed decisions and to choose materials under consideration of the absolute availability of resources, market constraints and the goals of sustainable development. The methods provide transparent estimates for the relative

[50] *Rare earths* are more abundant in the earth's crust than many other materials (Hedrick 2010; Humphries 2010). This is also highlighted by the very high reserve-to-production ration (see Chapter 4.2.1).

ranking of supply risks. The developed methods not only enhance the assessment of potential physical scarcity, but are apt to display current concerns and capture potential constraints of resource supply (e.g., rare earths that are commonly perceived as scarce and are now associated with a high ESP and EnSP). Decisions concerning the material choice will differ significantly when based on the newly developed methods rather than on conventional resource availability assessments, evaluating only the geologic availability.

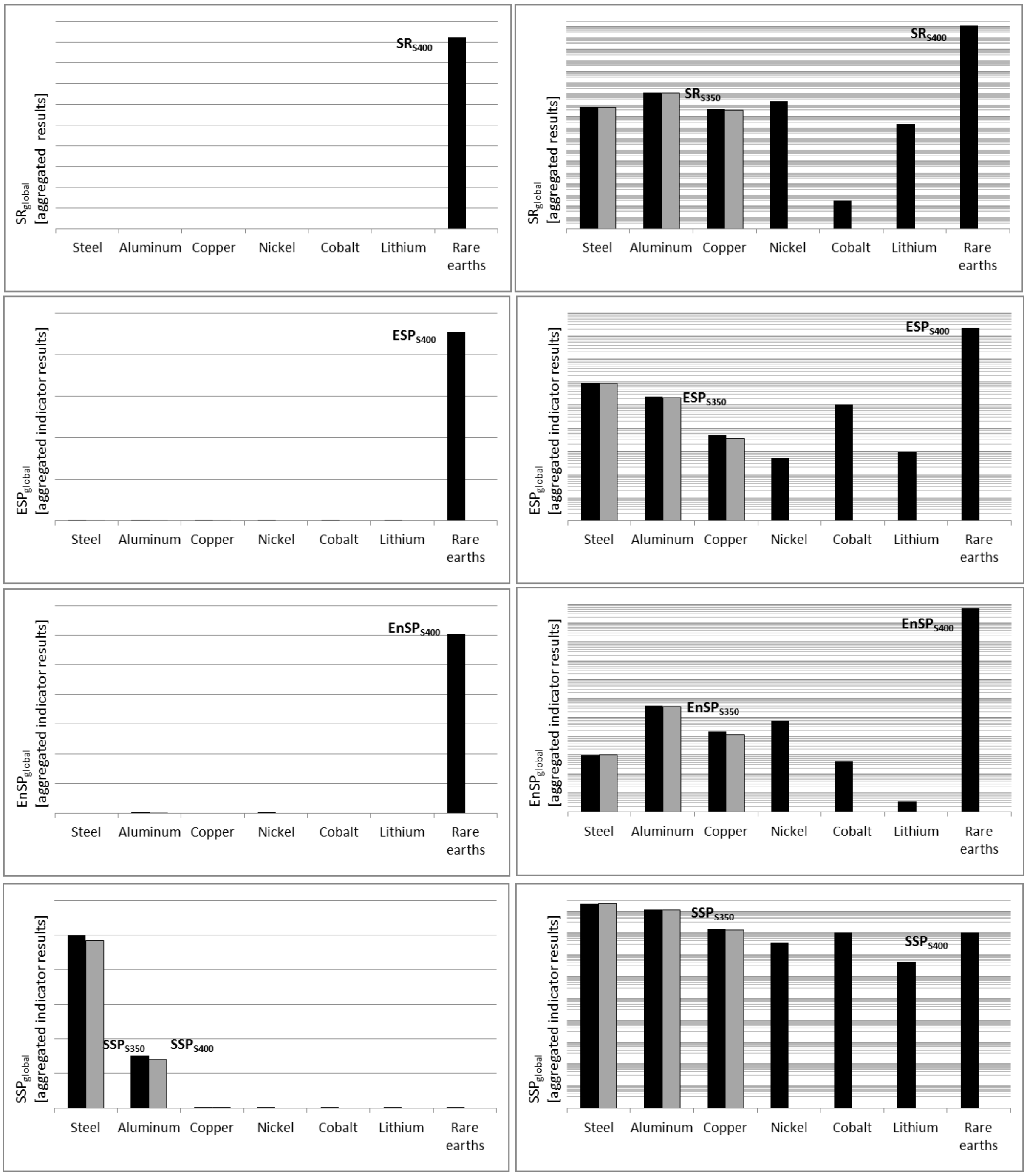

Figure 7.13: Case study results – ESP, EnSP, and SSP, normal scale (left) **and logarithmic scale** (right)

In the following the applicability of the methods in the context of current LCI databases is discussed. In the context of a holistic assessment, aiming at addressing the availability of resources and potential constraints by considering the entire supply chain and to incorporate a life cycle perspective, the link of the methodology to existing LCI databases would be of great benefit. Thereby, all materials involved in the upstream processes and connected to the production of the assessed metals could be evaluated, to uncover potential bottlenecks to supply and to uncover high depletion potentials associated with materials needed in the production process. However, LCI data available (e.g., P.E. International, ecoinvent) is also affected by the allocation step based on the economic value of materials. This allocation step is conducted on an ore level and depends on the composition of the respective deposits and affects not only the output, but also the input of the ore as such. Thus, the evaluation of the $ADP_{\text{ultimate reserves}}$ (based on an inventory of 1kg of each material) will lead to different results, than the evaluation of a materials inventory independent from the LCI. In Figure 7.14 this effect is displayed, by comparing $ADP_{\text{ultimate reserves}}$ characterization factors based on the characterization factors published by van Oers et al. (2002) (on a kilogram basis) and linked to the LCI associated with the production of 1kg of a material based on the GaBi database (Abell and Oppenheimer 2008; PE International 2013).

Even though the overall distribution seems to be similar, significant differences occur with regard to the absolute value for several materials. This is contrary to the expectation that all materials should have a comparably higher ADP, due to additional inputs considered in the inventory of the different materials. Furthermore, tin for example has a high $ADP_{\text{ultimate reserves}}$, is however associated with a very low depletion potential when linked to the LCI in the GaBi data base. This is due to the fact that the inventory of one kilogram of tin for example does not contain this amount of the material in the LCI, but significantly less.

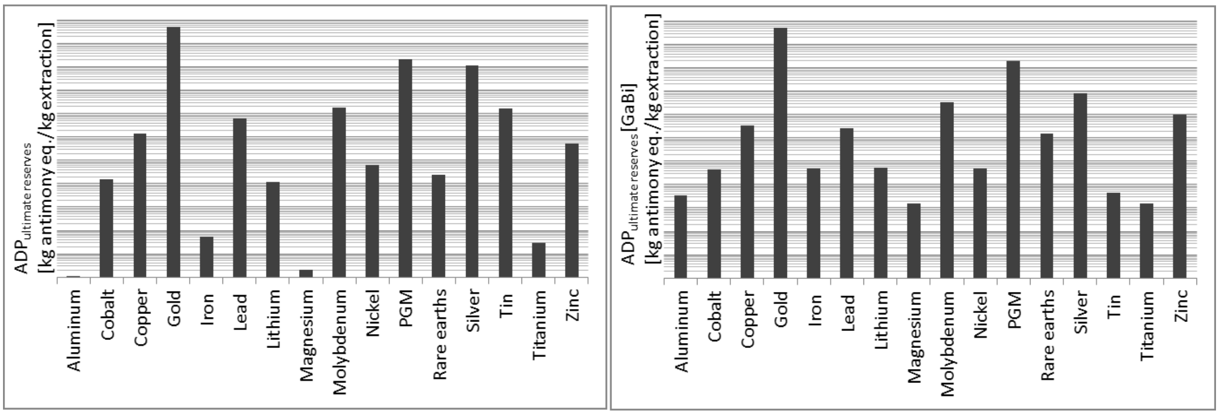

Figure 7.14: $ADP_{\text{ultimate reserves}}$ (van Oers et al. 2002) **vs. $ADP_{\text{ultimate reserves}}$ (linked to LCI)** (PE International 2013) (adapted to fit logarithmic scale)

As inconsistencies exist with regard to the existing LCI-data (due to correction of some values), no overall conclusion can be drawn. Thus, the informative value of assessments of resource depletion based on existing LCI-data needs to be questioned. In this dissertation, results are generated on a 'bill of materials' basis, and so far independent from LCI of products. A linkage of the developed models to existing LCI databases needs to be seen in the context of the described constraints and uncertainties.

In the context of sustainable development, long term resource provision needs to be secured and the assessment of physical resource availability is essential. To advance the assessment of physical availability was enhanced by proposing a new parameterization that accounts for the loss of a material rather than extraction from nature. Furthermore, this dissertation highlighted that the assessment needs to be complemented to make informed decisions on a product level. As availability of resources depends on a broad set of economic, environmental and social issues, this work provided a framework for the assessment of resource beyond existing models and beyond physical availability. Economic, social and environmental constraints related to resource provision are relevant for sustainable development and hence need to be an integral part of the LCSA framework and complement existing LCA models. All in all, neglecting the different dimensions of resource availability in the assessment of resource availability seems insufficient for achieving sustainable development.

The developed models provide new insights and deliver additional decision support for evaluating the availability of resources. As the models can be aligned to company goals and can be adapted to specific research needs, the evaluation of resource availability for product systems can be significantly enhanced. For the interpretation of the results it has to be kept in mind that only the potential risk is assessed. This means that the interpretation of the results always has to be seen in the context of current developments and the results should not be perceived as an absolute value outside of the specific context.

To obtain a better understanding of the issues raised in this dissertation and to exploit the potential of the developed methods addressed shortcoming of the methods need to be tackled in future research and an enhancement of the underlying models and data need to take place. An overview of recommendations for future research is outlined in the next chapter.

8 CONCLUSIONS AND OUTLOOK

In this chapter, the main aspects of the models to assess physical, economic, environmental and social resource scarcity are summarized and conclusions are drawn. Moreover, the results of this dissertation are discussed and remaining challenges are outlined.

8.1 Summary of main findings

Abiotic resources play an essential role in our society, and availability needs to be closely monitored. The amount of material available to society is influenced by physical realities of extraction, politics, economic circumstances and social or environmental performance. For achieving sustainable development the sustained provision of resources for current and future generation was identified as the key concern.

Based on the review of existing methods and their shortcomings, methodological challenges and needs were identified and addressed in this dissertation. The analysis has shown that most methods currently available for the assessment of resource availability focus on an assessment of the geologic stocks of resources and the efforts of their extraction. Traditional LCA only cover geological availability of resources. Recommendations based on LCA fail to recognize the complexity of resource provision and thus neglect possible trade-offs between environmental, social and economic constraints. Resource availability assessment needs to go beyond the currently established evaluation in LCA and shift from assessing availability as an environmental impact to defining resource availability as a sustainability problem.

In this dissertation various aspects of resource scarcity are surveyed and an operational framework was developed that allows for the consideration of different aspects of scarcity in the context of retaining material security for current and future generations. The broadening of the scope towards LCSA was identified as crucial to comprehensively evaluate resource provision capability. The comprehensive evaluation proposed in this dissertation distinguishes two different notions of scarcity: the potential depletion of resources, leading to physical scarcity of a resource in the longer term, and the potential resource scarcity provoked by risks along the supply chain of materials.

In a first step, existing approaches for the assessment of physical resource availability were reconsidered. The assumption that geologic stocks are generally the only source of material is refuted in the context of the functional (rather than environmental) value of abiotic resources. In order to allow for a more realistic assessment of physical material availability, a new parameterization of the characterization model for depletion of abiotic resources was introduced. The developed AADP model evaluates the availability of abiotic resources by introducing a new parameterization of the characterization model commonly used for assessing the depletion of abiotic resources. The model strives for addressing the ultimately extractable amount of resources, rather than the average concentration in the earth's crust. Furthermore, anthropogenic stocks are included into the characterization model. The developed approach is a relevant enhancement towards sustainable development, as not the extraction of resources should be of concern, but rather their dissipative use and loss. A comparison between AADP and conventional resource assessments by means of ADP revealed different results. Materials, such as mercury, with high anthropogenic stocks were identified as comparatively less critical than materials with low anthropogenic stocks. Furthermore, by means of the new parameterization metals like *cobalt*, which are perceived as critical for future technologies contribute more to the AADP category indicator results than to conventional ADP assessment. The new parameterization contributes to a more realistic assessment of the physical resource stock actually available for human needs.

In a second step, new models for the assessment of resource availability have been introduced aiming at enhancing the analysis of resource provision beyond physical resource stocks. To support material selection, the different dimensions of sustainability were included into the assessment of resource provision capability. Different methodologies were developed in this dissertation, accounting for the economic, environmental and social resource scarcity potential by considering potential constraints in the supply chain. The models went beyond the consideration of single indicators and provided aggregated risk scores for easy identification of high-risk materials. To enable an evaluation of risks a characterization model was developed, that included the definition of a threshold-value. By setting actual values in relation to identified thresholds the respective exceedance was determined, evaluating the probability that constraints to resource supply would occur. The methods were set up to reinforce the significance of risks in the context of material inventories and to uncover all potential risks associated with specific materials.

The comparative assessment of the different dimensions of resource scarcity revealed that resources do not have to be geologically scarce to be associated with high supply risks. For example, rare earths turned out to be associated with high supply risks, but are uncritical from a geologic perspective. Contrary to his finding, some physically scarce metals were associated with comparably low supply risks. Availability of resources differed significantly when economic, environmental or social aspects were taken into account beyond physical depletion.

The developed methods allow for a more realistic assessment of resource provision capability and complement and enhance current resource assessment. A detailed assessment of economic criteria influencing resource availability on a product level is essential to prevent disruptions within the supply chain Furthermore, in the context of attaining sustainability goals, environmental impacts and social aspects along the supply chain can effectively constrain resource supply and need to be incorporated into decision making. The developed methodologies can help to identify "hotspots" and risks associated with industrial resource use and to make material choices in line with sustainability goals. As verified by an exemplary case study the methodologies are apt for delivering more diversified results that represent not only long term concerns but also potential constraints to current resource supply. The methodologies add to current resource assessment practice and allow for the consideration of economic constraints as well as environmental and social performance of different materials.

The quantification of the different dimensions of scarcity delivers additional decision support and enables the identification of high risk materials in the context of retaining material security. As the proposed methods are oriented towards the comprehensive evaluation of resource availability in the context of LCSA guidance for sustainable choices of resources can be made. This is a noteworthy improvement compared to existing methodologies that mainly address only the environmental sustainability or are independent from evaluations of product systems. The developed models are applicable on a product level and can be linked to material inventories enabling easy implementation and integration into decision making. Based on the developed methodological framework, use of materials can be evaluated by taking their potential physical, economic, environmental, and social scarcity into account to incorporate availability and accessibility of resources into decision making.

Nevertheless, methodological and practical challenges remain, which have to be addressed by future research. The analysis of resource provision capability in this work is still based on several simplifying assumptions and is not capable to model the full inherent complexity of the global system.

8.2 Remaining challenges and recommendations

In this section remaining challenges are specified and future research needs are addressed. This dissertation proposed a methodological framework for the assessment of potential constraints to resource provision capability. This framework provides a basis for evaluating resource availability in the context of sustainability analyses. However, for the proper use and implementation of the methods additional research is needed. Below the most important aspects for future research are described. Hereby, immediate issues with regard to current methods and results as well as further enhancements of the methods are outlined.

Consideration of additional indicators to assess supply risks

So far, a limited set of criteria and indicators is assessed to determine the different supply risks in this work. The choice and definition of indicators aims to be as broad and complete as possible, but is restricted by the limited availability of methods and data, especially for determining environmental or social risks. For an enhancement of the developed methodologies and to increase the informative value for the results, additional aspects and indicators should be considered in future development of the methods. The evaluation of impacts on the environment and the identification of potential constraints beyond current impact assessment practice in LCA are necessary. For example, additional information on environmental impacts of resource production need to be considered, including new models and aspects such as land-use, water use, etc. The method developed in this work has to be seen as a basis and first step towards a more detailed and comprehensive assessment in the future.

Review and enhancement of underlying data for the assessment of supply risks

The applicability and validity of the developed methods is currently restricted due to limited availability of consistent and comprehensive data. Several indicators are already available for the assessment of the economic dimension of supply risk. Data used is reliant and based on commonly accepted sources. While additional criteria could be considered for the assessment of the ESP, existing coverage already seems to enable a realistic assessment of potential economic constraints in the supply chain. The number of readily applicable characterization methods for the assessment of the EnSP is limited. However, available methods are scientifically valid and commonly applied for the assessment of environmental impacts. Furthermore, the underlying data retrieved from LCA databases is associated with high uncertainties and results have to be interpreted in the context of these limitations. The data used as a basis for the evaluation of the social dimension of supply risk are associated with significant shortcomings. The results of the SSP have to be interpreted in the context of the high uncertainty of results. Due to limited availability of reliable and quantitative indicators, assumptions and exceptions are made for the calculation of the average country risks. Even though the SHDB presents current best available practice, data and indicators need to be seen in the context of these shortcomings and the general applicability of these average risk values data for the assessment of the SSP needs to be questioned. Reliability and completeness of underlying data needs to be improved for increasing the significance of the assessment potential social constraints to resource supply.

Definition of available resource stocks

The AADP model is a promising approach to provide a more realistic picture of the actual physical availability of metals. While the model and the underlying approach as such are applicable and targeted, the determination of geologic and anthropogenic stocks of minerals is highly complex and associated with high uncertainties. Currently used data relies on commonly utilized and available databases and can thus be seen as a best estimate. However the limited availability of data for the assessment of resource stocks currently constrains the practical application of the model.

For determining the future availability of materials, the amount of a given metal that is judged to be extractable over the long term needs to be assessed. The knowledge about an ore deposit does not necessarily mean that it will or can be exploited and available estimates for the quantification of extractable resource stocks are controversial. The classification of the anthropogenic stock is also complicated and requires thorough analysis as it occurs in many different states within the anthroposphere. Furthermore, factors for determining the dissipation of individual materials are missing. This makes an exact quantification difficult. Besides, the quality of recovered materials might not be sufficient for certain applications and downgrading of materials needs to be assessed in the context of defining the functional value stored in anthropogenic resource stocks. Consequently, current characterization factors still show weaknesses due to data uncertainties especially on the global level. Further research has to be done in this area, to provide a better estimate of the availability of stocks in nature and anthroposphere.

Reconsideration of value choices

The selection of aspects and the determination of targets are by definition value choices. Results of the comprehensive analysis depend on the choice and number of aspects considered and the underlying methods used for calculating indicators. The actual risk associated with certain materials in a specific product system varies in line with the choices made. As shown earlier, different thresholds can have effects on the overall results. The definition of thresholds is based on value choices and leaves large room for interpretation.

This study relies on best estimates for the determination of the targets. While thresholds are inherent to many indicators used for determining the ESP or can be derived from average global values, the definition of thresholds to be used in assessing the EnSP and SSP is more complex. It is hard to define thresholds above which environmental or social risks occur as no data is available to make generally applicable statements. Thus, in this study best estimates are used with the aim to uncover all potential risks. However, the developed framework supports the system specific adaption of targets to achieve high relevance and informative value of the results.

The ranking of material scarcity presented in this dissertation has to be seen in the context of the value choices made. For future application and customization of the methods, additional guidance needs to be provided to ensure compliance with sustainability goals.

More detailed exploration of the supply chain

For sustainable resource management all life cycle stages, from resource extraction through production until resource provision need to be analyzed. Potential constraints to resource supply can occur at any stage of the supply chain. So far, only the mining stage was addressed, neglecting potential bottlenecks at other supply chain stages. Thus, the results have to be seen in the context of this system definition. In future research, an extension of the assessment towards additional supply chain stages is required including further processing steps.

Current assessment focuses on the resource provision stage, including the relevant supply chain stages up to the provision of the specific material for further use in products. However, decisions on a product level often involve the provision of already manufactured products, rather than materials as such. Bottlenecks consequently can also occur at the manufacturing level and refer to the provision of materials incorporated in intermediate products (e.g., 73% of the cathode production for lithium-ion batteries takes place in Japan). To what extent a consideration of these additional stages is possible and whether technology specific risk scores and bottlenecks for different materials can be developed needs to be assessed in future studies.

Consideration of secondary material

Recycling of materials is a key strategy for a sustainable future and acknowledged as an important source of materials. So far, the relevance of secondary resources has mainly been discussed in the context of depletion. The potential availability of secondary resources and their relevance on considerations of resource depletion has been highlighted in this work. However, as outlined in previous chapters, secondary resources underlie similar constraints to supply than primary materials. Recycling is often perceived as a way to mitigate negative impacts on the environment but the supply of secondary material might be associated with high social or economic risks. Thus, secondary materials need to be addressed as separate "resource class" to comprehensively determine environmental, economic, and social constraints associated with secondary resources. Such a separate evaluation enables the comparison of secondary and primary resources and broadens the basis for sustainable decision making.

Expanding the material portfolio

So far, only a limited material portfolio is addressed in this dissertation and the methods have only been applied to metals. However, the methods are also applicable for evaluating fossil energy fuels and other abiotic resources. Additional data needs to be provided and the proposed methods need to be tested in future case studies on a product level. Furthermore, a higher level of granularity is needed. *PGM* and *rare earth* elements should be assessed with regard to the individual metals, rather than as a group.

In future studies the complexity of material choices needs to be acknowledged. The assessment of resource availability needs to go beyond mineral resources. In many situations a non-metal can be a better alternative. Thus, for assessing which uses are appropriate the addressed resource portfolio needs to be expanded. Especially in the context of the aim that non-renewable resources should be substituted by renewable resources. The assessment of biotic resource availability can be developed based on the models proposed in this dissertation. However, different characteristics will have to be considered and current models need to be adapted and necessary add-ons have to be made.

Implementation in current databases

In the context of product systems, the developed methods need to be linked to the respective material inventories. Integration in and application to current LCI-databases would enable the evaluation of supply risks in the entire life cycle of materials. However, as of the time being this is not possible due to allocation applied within existing databases and inconsistencies that exist with regard to the material inventories. Thus, the extent to which existing databases can actually be used in praxis to evaluate the amount of potentially scarce resource used needs to be questioned. However, this is a database problem and not a problem of the here proposed approach.

For broad application of the assessment of resource availability and for integration of resource availability into decision making reliant databases are required. Available LCI - databases need to be adapted to enable an evaluation of resource availability.

Temporal sensitivity

The supply risks addressed in this dissertation were captured only at a specific point in time providing a snapshot of the current situation. The economic risk associated with material supply can change as political situations change or new mines are opened up. Furthermore, social and environmental risks can change over time, in line with technological progress and social circumstances. As mentioned before the base period of the study can affect value and relevance of indicators and periodical updates and a reconsideration of data and thresholds is essential. A meaningful timeframe needs to be identified for periodically updates of the data. Further sensitivity analysis of the underlying data need to be conducted.

To obtain a better understanding of the issues raised in this dissertation and to increase the practical relevance and informative value of the developed methodologies, the complexity of societies and metal demand and supply need to be taken into account. The methodological and practical shortcomings described above need to be revisited in future studies and the application of the proposed framework for assessing resource availability needs to be tested further by means of case studies.

The assessment of resource provision capability needs to be incorporated into early stages of product development and provides a basis for material choices in the context of sustainable development. The developed methods do not aim at displaying the truth as there is not one truth. The models have to be seen in the context of their scope to identify bottlenecks or hotspots within the supply chain of resources or to detect the contribution of resource use to potential depletion. By developing a model towards LCSA this enhances current resource assessment practice. The assessment of resource availability in the framework of LCSA presents a promising enhancement of current assessment practice and supports the management and sustainment of resources.

REFERENCES

Abell L, Oppenheimer P (2008) World Lithium Resource Impact on Electric Vehicles. Naval Postgraduate School, Monterey, CA

Achzet B, Reller A, Zepf V, Rennie C, Ashfield M, Simmons J (2011) Materials criticality to the energy industry. An introduction. University of Augsburg, BP, ON Communication, Augsburg

Acton PM, Fox JF, Campbell JE, Jones AL, Rowe H, Martin D, Bryson S (2011) Role of soil health in maintainng environmental sustainability of surface coal mining. Environmental Science & Technology 45 (23):10265-10272

Alonso E, Gregory J, Field F, Kirchain R (2007) Material availability and the supply cahin: risks, effects, and responses. Environmental Science & Technology 41 (19):6649-6656

Althaus H-J, de Haan P, Scholz R (2009) Traffic noise in LCA, Part 1: state-of-science and requirement profile for consistent context-sensitive integration of traffic noise in LCA. International Journal of Life Cycle Assessment 14 (6):560-570

Angerer G, Erdmann L, Marscheider-Weidemann F, Scharp M, Lüllmann A, Handke V, Marwerde M (2009a) Rohstoffe für Zukunftstechnologien. ISI-Schriftenreihe "Innovationspotenziale". Fraunhofer IRB Verlag, Stuttgart

Angerer G, Marscheider-Weidemann F, Wendl M, Witschel M (2009b) Lithium für Zukunftstechnologien. Fraunhofer ISI, Karlsruhe

Apple Inc. (2013) Apple supplier responsibility. 2013 Progress Report.

Arrow KJ (1965) Aspects of the Theory of Risk Bearing. Yrjö Jahnssonin Säätiö, Helsinki

Aspermont Media (2013) Mining 101. Mining Journal http://www.mining-journal.com/knowledge/Mining-101

Auty RM (1993) Sustaining development in mineral economics RTZ, London and New York

Ayres R, Ayres L, Rade I (2003) The life cycle of copper, its co-products and by-products. Springer Science + Business Media, Dordrecht

Azapagic A (2004) Developing a framework for sutainable development indicators for the mining and minerals industry. Journal of Cleaner Production 12 (6):639-662

Bardi U (2011) Revisiting the limits to growth. Springer, New York

Bardi U (2013) Der geplünderte Planet - Die Zukunft der Menschen im Zeitalter schwindender Ressourcen. oekom, München

Bardt H, Kempermann H, Lichtblau K (2013) Rohstoffe für die Industrie. Institut der deutschen Wirtschaft Köln e.V., Köln

Barnett HJ, Morse C (1963) Scarcity and growht; the economics of natural resource availability. Resources for the future. John Hopkins Press, Washington, DC

Barton PB (1983) Unconventional mineral deposits - a challenge to geochemistry. In: Shanks WC (ed) Cameron volume on unconventional mineral deposits. Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, pp 3-14

Baumann H, Tillman A-M (2004) The Hitch Hiker's Guide to LCA. Studentlitteratur AB, Lund

BDI (2010) Übersicht über besthende Handels- und Wettbewerbsverzerrungen auf den Rohstoffmärkten. Bundesverband der Deutschen Industrie e.V. , Berlin

Behrens A, Giljum S, Kovanda J, Niza S (2007) The material basis of the global economy - Worldwide patterns of natural resource extraction and their implications for sustainable resource use policies. Ecological Economics 64 (2):444-453

Bell JE, Autry CW, Mollenkopf DA, Thornton LM (2012) A natural resource scarcity typology: Theoretical foundations and strategic implications for supply chain management. Journal of Business Logistics 33 (2):158-166

Benoît-Norris C, Aulision Cavan D, Norris G (2012) Identifying social impacts in product supply chain: overview and applicaiton of the Social Hotspot Database. Sustainability 4 (9):1946-1965

Benoît-Norris C, Norris GA, Aulisio-Cavan D (2013) Social hotspot database - supporting documentation. New Earth, Boston

Benoît C, Norris GA, Valdivia S, Ciroth A, Moberg A, Bos U, prakash S, Ugaya C, Beck T (2010) The guidelines for social life cycle assessment of products: just in time! International Journal of Life Cycle Assessment 15 (2):156-163

Benoît Norris C (2014) Data for social LCA. International Journal of Life Cycle Assessment 19 (2):261-265

Bentley RW (2002) Global oil & gas depletion: an overview. Energy Policy 30 (3):189-205

Berger M, Finkbeiner M (2011) Correlation analysis of life cycle impact assessment indicators measuring resource use. International Journal of Life Cycle Assessment 16 (1):74-81

Berger M, Warsen J, Krinke S, Bach V, Finkbeiner M (2012) Water footprint of European cars: potential impacts of water consumption along automobile life cycles. Environmental Science & Technology 46 (7):4091-4099

Bernhardt ES, Lutz BD, King RS, Fay JP, Carter CE, Helton AM, Campagna D, Amos J (2012) How many mountains can we mine? Assessing the regional degradation of Central Appalachian riversy by surface coal mining. Environmental Science & Technology 46 (15):8115-8122

BGR (2007) Rohstoffwirtschaftliche Steckbriefe für Metall- und Nichtmetallrohstoffe. Bundestanstalt für Geowissenschaften und Rohstoffe, Hannover

Binder CR, Graedel TE, Reck B (2006) Explanatory variables for per capita stocks and flows of copper and zinc. Journal of Industrial Ecology 10 (1-2):111-132

Borchert I, Gootiiz B, Mattoo A (2012a) Guide to the services trade restrictions database. Policy research working paper. The Worldbank, Washington, DC

Borchert I, Gootiiz B, Mattoo A (2012b) Policy barriers to international trade in services: new empirical evidence. Policy research working paper. The WorldBank, Washington, DC

Bösch ME, Hellweg S, Huijbregts M, Frischknecht R (2007) Applying cumulative exergy demand (CExD) indicators to the ecoinvent database. International Journal of Life Cycle Assessment 12 (3):181-190

Brand KW (2002) Politik der Nachhaltigkeit. Edition Sigma, Berlin

Brentrup F, Küsters J, Lammel J, Kuhlmann H (2002a) Impact Assessment of Abiotic Resource Consumption. International Journal of LCA 7 (5):301-307

Brentrup F, Küsters J, Lammel J, Kuhlmann H (2002b) Impact assessment of abiotic resource consumption. International Journal of Life Cycle Assessment 7 (5):301-307

Brown TJ, Idoine NE, Hobbs SF, Mills AJ (2014) European mineral statistics 2008-2012. British Geological Survey Nottingham

Brown WM (2002) The meaning of scarcity in the 21st century: drivers and constraints to the supply of minerals using regional, national and global perspectives. Volume IV, Sociocultural and institutional drivers and constraints to mineral supply. U.S. Geological Survey Open-File Report 02-333, Washington, DC

Brunekreef B, Holgate ST (2002) Air pollution and health. The Lancet 360 (9341):1233–1242. doi:http://dx.doi.org/10.1016/S0140-6736(02)11274-8

Brunner PH, Rechberger H (2004) Practical Handbook of Material Flow Analysis. Lewis Publishers, Boca Raton, FL

Buchert M, Schüler D, Bleher D (2009) Critical metals for future sustainable technologies and their recycling potential. Sustainable innovation and technology transfer industrial sector studies. United Nations Environmentl Programme (UNEP), Öko-Institut e.V., Darmstadt, Paris

Buijs B, Sievers H (2012) Resource security risks in perspective - complexitiy and nuance. POLINARES working paper n. 33. POLINARES - EU policy on natural resources, Dundee

Buijs B, Sievers H, Tercero Espinoza LA (2012) Limits to the critical raw materials approach. Waste and Resource Management 165 (4):201-208

Burns A, van Rensburg TJ (2012) Global economic prospects. The World Bank, Washington, DC

Butterman W, Carlin J (2004) Antimony. Mineral Commodity Profiles. U.S. Geological Survey, Washington, DC

BUWAL (1998) Bewertung in Ökobilanzen mit der Methode der ökologischen Knappheit - Ökofaktoren 1997. Schriftenreihe Umwelt, Nr. 297 - Ökobilanzen. Federal office for environment forest and landscape, Bern

Chapman PF, Roberts F (1983) Metal Resources and Energy. Butterworths, London

Chemetall (2009) Lithium Applications and Availability. Chemetall Statement.

Clark C, Martin R, van Kempen E, Alfred T, Head J, Davies HW, Haines MM, Barrio IL, Matheson M, Stansfeld SA (2006) Exposure-effect relations between aircraft and road traffic noise exposure at school and reading comprehension – The RANCH project. Am J Epidemiol 163 (1):27-37

Classen M, Althaus H, Blaser S, Scharnhorst W, Tuchschmid M, Jungbluth N, Faist Emmenegger M (2007) Life cycle inventories of metals. Ecoinvent reports v2.0. Dübendorf

CML (2013) CML - IA 4.2 edn. Institut of Environmental Sciences Leiden University, Leiden

Craig JR, Rimstidt JD (1998) Gold production history of the United States. Ore Geology Reviews 12 (6):407-464

Crowson PCF (2011) Mineral reserves and future minerals availability. Minerals Economics 24 (1):1-6

Cucurachi S, Heijungs R, Ohlau K (2012) Towards a general framework for including noise impacts in LCA. International Journal of Life Cycle Assessment 17 (4):471-487

Curran M, de Baan L, de Schryver AM, van Zelm R, Hellweg S, Koellner T, Sonnemann G, Huijbregts MAJ (2011) Toward meaningful end points of biodiversity in life cycle assessment. Environmental Science & Technology 45 (1):70–79

Dahlbo H, Koskela S, Pihkola H, Nors M, Federly M, Seppälä J (2013) Comparison of different normalised LCIA results and their feasibility in communication. International Journal of Life Cycle Assessment 18 (4):850-860

Daimler AG (2012) Personal communication. Berlin

Daly HE (1990) Toward some operational principles of sustainable development. Ecological Economics 2 (1):1-6

Defra (2012) A Review of National Resource Strategies and Research. Department for Environment, Food and Rural Affairs, London

Deutsches Kupferinstitut (2011) Vorkommen und Gewinnung. http://www.kupfer-institut.de/front_frame/frameset.php3?client=1&lang=1&idcat=34&parent=14. Accessed 22.02.2011

Dewulf J, Bösch ME, de Meester B, van der Vorst G, van Langenhove H, Hellweg S, Huijbregts MAJ (2007) Cumulative exergy extraction from the natural environment (CEENE): a comprehensive life cycle impact assessment method for resource accounting. Environmental Science & Technology 41 (24):8477-8483

Dewulf J, Van Langenhove H, Muys B, Bruers S, Bakshi BR, Grubb GF, Paulus DM, Sciubba E (2008) Exergy: Its potential and limitations in environmental science and technology. Environmental Science & Technology 42 (7):2221-2232

DeYoung Jr. JH, Barton PB, Boulègue J, Dahmen P, Gocht WRA, Kürsten MOC, Phillips WGB, Price RA, Sheldon RP, Skinner BJ, Vogt JH, Alten EGLv, Weisser JD, Williams N (1987) Assessment of non-energy mineral resources. In: McLaren DJ, Skinner BJ (eds) Resources and world development. Dahlem Workshop Reports. John Wiley & Sons Limited, Dahlem, pp 508-523

Ditsele O, Awuah-Offei K (2012) Effect of mine characteristics on life cycle impacts of US surface coal mining. International Journal of Life Cycle Assessment 17 (3):287-294

DOE (2010) Critical materials strategy. U.S. Department of Energy, Washington, DC

DOJ, FDT (2010) Horizontal Merger Guidelines §5.2. The United States Department of Justice and the Federal Trade Commission, Washington, DC

Dong Y, Laurent A, Hauschild MZ (2013) Recommended assessment framework, characterisation models and factors for environmental impacts and resource use. Report prepared within the Seventh Framework Project of the European Union - Development and applicaiton of a standardized methodology for the prospective sustianabiltiy assessment of technologies.

Dreyer LC, Hauschild MZ, Schierbeck J (2010) Characterisation of social impacts in LCA. International Journal of Life Cycle Assessment 15 (3):247-259

Dreyer LC, Hauschild MZ, Shierbeck J (2006) A framework for social life cycle impact assessment. International Journal of Life Cycle Assessment 11 (2):88-97

Durucan S, Korre A, Munoz-Melendez G (2006) Mining life cycle modelling: a cradle-to-gate approach to environmental management in the minerals industry. Journal of Cleaner Production 14 (12-13):1057-1070

ecoinvent Centre (2010) http://www.ecoinvent.org/. Accessed 12 April 2010

Edelstein DL (2013) 2011 Minerals Yearbook: Copper. U.S. Geological Survey, U.S. Department of the Interior, Washington, DC

Erdmann L, Behrendt S (2010) Kritische Rohstoffe für Deutschland. Institut für Zukunftsstudien und Technologiebewertung (IZT), Berlin

Erdmann L, Graedel TE (2011) Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses. Environmental Science & Technology 45 (18):7620-7630

European Commission (2005) Thematic strategy on the sustainable use or natural resources. COM (2005) 670. Brussels

European Commission (2008) A special place for children in EU externa action. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committe of the Regions, COM(2008) 55. Brussels

European Commission (2010a) Critical raw materials for the EU. Report of the ad-hoc working group on defining critical raw materials, European Commission, Brussels

European Commission (2010b) International Reference Life Cycle Data System (ILCD) Handbook - General guide for life cycle assessment -detailed guidance. EUR 24708 EN. Publications Office of the European Union, Luxembourg

European Commission (2010c) International Reference Life Cylce Data System (ILCD) Handbook - Framework and Requirements for Life Cycle Impact Assessment Models and Indicators. EUR 24709 EN. Luxembourg

European Commission (2011a) International Reference Life Cycle Data System (ILCD) Handbook - Recommendations for life cycle impact assessment in the European context. Publications Office of the European Union, Luxemburg

European Commission (2011b) A resource-efficient Europe - Flagship initiative under the Europe 2020 strategy. COM(2011) 21. Brussels

European Commission (2011c) Roadmap to a resource efficient Europe. COM (2011) 571 final. Brussels

European Commission (2012) Options for Resource Efficiency Indicators. European Commission, Directorate-general Environment, Brussels

European Commission (2013a) Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations.

European Commission (2013b) Science for environment policy in-depth report: Resource efficiency indicators. Science Communication Unit, University of the West of England, Bristol

Finkbeiner M (ed) (2011) Toward Life Cycle Sustainability Management. Springer Science + Business Media, Berlin

Finkbeiner M, Ackermann R, Bach V, Berger M, Brankatschk G, Chang Y-J, Grinberg M, Lehmann A, Martínez-Blanco J, Minkov N, Neugebauer S, Scheumann R, Schneider L, Wolf K (2014) Challenges in life cycle assessment: An overview of current gaps and research needs. In: Klöpffer W (ed) LCA Compendium - The Complete World of Life Cycle Assessment –Volume 1: Background and Future Prospects in Life Cycle Assessment. Springer, Dodrecht,

Finkbeiner M, Inaba A, Tan RBH, Christiansen K, Klüppel H-J (2006) The new international standards for life cycle assessment: ISO 14040 and ISO 14044. International Journal of Life Cycle Assessment 11 (2):80-85

Finkbeiner M, Schau EM, Lehmann A, Traverso M (2010) Towards life cycle sustainability assessment. Sustainability 2 (10):3309-3322

Finnveden G (1996) Resources and related impact categories. In: Udo de Haes HA (ed) Towards a methodology for life-cycle impact assessment. Society of Environmental Toxicology and Chemistry (SETAC), Brussels, pp 39-48

Finnveden G (2005) The resource debate needs to continue. International Journal of Life Cycle Assessment 10 (5):372

Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in Life Cycle Assessment. Journal of Environmental Management 91 (1):1-21

Finnveden G, Hofstetter P, Bare J, Basson L, Ciroth A, Mettier T, Seppälä J, Johanson J, Norris G, Volkwein S (2002) Normalization, grouping and weighting in life cycle impact assessment In: Udo de Haes HA, Finnveden G, Goedkoop M et al. (eds) Life-cylce impact assessment: striving towards best practice. Published by the Society of Environmental Toxicology and Chemistry (SETAC), Pensacola, FL

Finnveden G, Östlund P (1997) Exergies of natural resources in life cycle assessment and other applications. Energy 22 (9):923-931

Frischknecht R (2003) Ecoinvent databased methodology. Paper presented at the Special LCA forum, Lausanne, December 5, 2003

Frischknecht R, Büsser-Knöpfel S (2013) Swiss Eco-Factors 2013 according to the Ecological Scarcity Method. Methodological fundamentals and their applicaiton in Switzerland. Environmental studies no. 1330. Federal Office for the Environment, Bern

Frischknecht R, Steiner R, Jungbluth N (2009) The Ecological Scarcity Method: Eco-Factors 2006 - A method for impact assessment in LCA. Environmental studies no. 0906. Federal Office for the Environment (FOEN), Bern

Fritsche UR, Jenseit W, et al. (1999) Methodikfragen bei der Berechnung des Kumulierten Energieaufwands (KEA). Institut for angewandte Ökologie e.V. , Darmstadt

Frondel M, Angerer G, Buchholz P, Grösche P, Huchtemann D, Oberheitman A, Peters J, Vance C, Sartorius C, Röhling S, Wagner M (2006) Trends der Angebots- und Nachfragesituation bei mineralischen Rohstoffen. Rheinisch-Westfälisches Institut für Wirtschaftsforschung, Fraunhofer-Institut für System- und Innovationsforschung, Bundesanstalt für Geowissenschaften und Rohstoffe, Berlin

Frondel M, Grösche P, Huchtemann D, Oberheitmann A, Peters J, Angerer G, Sartorius C, Buchholz P, Röhling S, Wagner M (2005) Trends der Angebots- und Nachfragesituation bei mineralischen Rohstoffen. Rheinisch-Westfälisches Institut für Wirtschaftsforschung (RWI Essen), Fraunhofer-Institut für System- und Innovationsforschung (ISI), Bundesanstalg für Geowissenschaften und Rohstoffe (BGR), Essen

Gerber L, Warden-Fernandez J (2012) The institutional framework for access to mineral resources. POLINARES working paper n. 56. University of Dundee, Dundee

Gerst MD, Graedel TE (2008) In-Use Stocks of Metals: Status and Implications. Environmental Science & Technology 42 (19):7038-7045

GHGm (2008) Social and Environmental Responsibility in Metals Supply to the Electronic Industry. GreenhouseGasMeasurement.com (GHGm), Guelph, Canada

Giljum S, Behrens A, Hinterberger F, Lutz C, Meyer B (2008) Modelling scenarios towards a sustainable use of natural resourcs in Europe. Environmental Science & Policy 11 (3):204-216

Giljum S, Burger E, Hinterberger F, Lutter S (2009) A comprehensive set of resource use indicators from the micro to the macro level. SERI Working Paper No. 9. Sustainable Europe Research Institute (SERI), Vienna

Giljum S, Burger E, Hinterberger F, Lutter S, Bruckner M (2011) A comprehensive set of resource use indicators from the micro to the macro level. Resources, Conservation and Recycling 55 (3):300-308

Giurco D, Cooper C (2012) Mining and sustainability: asking the right questions. Minerals Engineering 29:3-12

Giurco D, Prior T, Mudd GM, Mason L, Behrisch J (2010) Peak minerals in Australia: a review of changing impacts and benefits. Institute for sustainable Futures (University of Technology) and Department of Civil Engineering (Monash University), Sydney

Global Reporting Initiative (2013) Sustainability reporting guidelines. Amsterdam

Goedkoop M, Heijungs R, Huijbregts M, Schryver AD, Struijs J, Zelm Rv (2008) ReCiPe 2008: A life cycle impact assessment method which compreises harmonised category indicators at the midpoint and the endpoint level. Pré Consultants, CML, RUN, RIVM, Amersfoort

Goedkoop M, Spriensma R (2000) The eco-indicator 99 - a damage oriented method for life cycle impact assessment. vol 2. PRé Consultants B.V., Amersfoort

Gontier M, Balfors B, Mörtberg U (2006) Biodiversity in environmental assessment - Ccurrent practice and tools for prediction. Environ Impact Assess Review 26 (3):268–286

Goodland R (1995) The concept of sustainability. Annual Review of Ecology and Systematics 26:1-24

Gordon RB, Bertram M, Gradel TE (2007) On the sustainability of metal supplies: A response to Tilton and Lagos. Resource Policy 32 (1-2):24-28

Gordon RB, Bertram M, Graedel TE (2006) Metal stocks and sustainability. PNAS 103 (5):1209-1214

Gordon RB, Koopmans TC, Nordhaus WD, Skinner BJ (1987) Towards a new iron age? Harvard University Press, Cambride, MA

Govett MH, Govett GJS (1976) Defining and measuring world mineral supplies. In: Govett GJS, Govett MH (eds) World mineral supplies - assessment and perspective. Elsevier Scientific Publishing Company, Amsterdam, pp 13-36

Graedel T, Allwood J, Birat J-P, Bucher M, Hagelüken C, Reck B, et al. (2011a) What do we know about metal recycling rates? Journal of Industrial Ecology 15 (3):355-366

Graedel TE, Barr R, Chandler C, Chase T, Choi J, Christofferson L, Friedlander E, Henly C, Jun C, Nassar NT, Schechner D, Warrne S, Yang M-y, Zhu C (2012a) Methodology of Metal Criticality Determination. Environmental Science & Technology 46 (2):1063-1070

Graedel TE, Barr R, Chandler C, Chase T, Choi J, Christofferson L, Friedlander E, Henly C, Jun C, Nassar NT, Schechner D, Warrne S, Yang M-y, Zhu C (2012b) Methodology of Metal Criticality Determination - Supporting information.

Graedel TE, Barr R, Cordier D, Enriquez M, Hagelüken C, Hammond NG, Kesler S, Mudd G, Nassar N, Peacey J, Reck BK, Robb L, Skinner B, Turnbull I, Santos RV, Wall F, Wittmer D (2011b) Estimating Long-Run Geological Stocks of Metals. UNEP Internationl Panel on Sustainable Resource Management, Paris

Graedel TE, Erdmann L (2012) Will material scarcity impede routine industrial use? MRS Bulletin 37 (4):325-331

Graedel TE, Gunn G, Tercero Espinoza L (2014) Metal resources, use and criticality. In: Gunn G (ed) Critical Metals Handbook. John Wiley & Sons, West Sussex, pp 1-19

Graedel TE, Harper EM, Nassar NT, Reck BK (2013) On the materials basis of modern society. PNAS Early edition. doi:10.1073/pnas.1312752110

Graedel TE, Klee RJ (2002) Getting serious about sustainability. Environmental Science & Technology 36 (4):523-529

Greco S, Wilson A, Spengler J, Levy J (2007) Spatial patterns of mobile source particulate matter emissions-to-exposure relationships across the United States. Atmospheric Environment 41 (5):1011-1025

Griefahn B, Marks A, Robens S (2006) Noise emitted from road, rail and air traffic and their effects on sleep. Journal of Sound and Vibration 295 (1–2):129–140

GTAP Data Bases: Detailed Sectoral List (2013) Global Trade Analysis Project (GTAP). https://www.gtap.agecon.purdue.edu/databases/contribute/detailedsector.asp.

Guinée J, Heijungs R (1995) A proposal for the definition of resource equivalency factors for use in product LCA. Environmental Toxicology and Chemistry 14 (5):917-925

Guinée JB (1995) Development of a methodology for the environmental life-cycle assessment of products. Leiden University, Leiden

Guinée JB, Bruijn H, van Duin R, Gorree M, Heijungs R, Huijbregts M, Huppes G, Kleihn R, de Koning A, van Oers L, Sleeswijk A, Suh S, Udo de Haes HA (eds) (2002) Handbook on life cycle assessment- an operational guide to the ISO standards. Kluwer Academic Publishers, Dordrecht

Guinée JB, de Bruijn H, van Duin R, Gorree M, Heijungs R, Huijbregts MAJ, Huppes G, Kleijn R, de Koning A, van Oers L, Sleeswijk AW, Suh S, Udo de Haes HA (2001) Life cycle assessment - An operational guide to the ISO standards, Part 2b. Centre of Environmental Science - Leiden University (CML), Leiden

Gupta C, Krishnamurthy N (1992) Extractive metallurgy of rare earths. International Materials Review 37 (1):197-248

Hagelüken C (2005) Autoabgaskatalysatoren. Expert Verlag, Renningen

Hagelüken C, Meskers CEM (2010) Complex Life Cycles of Precious and Special Metals. In: Graedel TE, Voet Evd (eds) Linkages of Sustainability. MIT Press, Cambridge, pp 163-197

Hauschild M, Goedkoop M, Guinée J, Heijungs R, Huijbregts M, Jolliet O, Margni M, de Schryver A, Humbert S, Laurent A, Sala S, Pant R (2013) Identifying best existing practice for characterization modelling in life cycle impact assessment. International Journal of Life Cycle Assessment 18 (3):683-697

Hauschild M, Wenzel H (1998) Environmental assessment of products, volume 2 - scientific backgrounds. Chapman & Hall, New York

Hedrick JB (2010) Rare earths. Mineral Commodity Summaries. U.S. Geological Survey,

Heidelberg Institute for International Conflict Research (2011) Conflict barometer. Heidelberg

Heijungs R, Guinée J, Huppes G (1997) Impact categories for natural resources and land use. CML Report 138. Leiden University, Centre of Environmental Science (CML), Leiden

Heinz H. Pariser (2011) Alloy Metals & Steel Market Reserch. www.heinzpariser.de.

Henley S, Allington R (2013) PERC, CRIRSC, and UNFC: minerals reporting standards and classifications. European Geologist 36:49-54

Henzen C (2008) The impact of land use on biodiversity in the framework of life cycle assessment. University of Basel, Basel

Hewett DF (1929) Cycles in metal production. In: Transactions of the American Institut of Mining and Metallurgical Engineers. Harvard University, New York, pp 65-98

Hill C (2011) An introduction to sustainable resource use. Earthscan Ltd. , London

Hill VG, Sehnke ED (2006) Bauxite. In: Kogel JE, Trivedi NC, Barker JM, Krukowski ST (eds) Industrial Minerals and Rocks. SME, Littleton, Colorado, pp 135-147

Hischier R, Weidema B (2010) Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3. ecoinvent centre, St. Gallen

Hollender R, Schultz J (2010) Bolivia and its lithium - Can the "Gold of the 21st Century" help lift a nation out of poverty? Democracy Center, Cochabamba

Humbert S, De Schryver A, Bengoa X, Margni M, Joliet O (2012) IMPACT 2002+: User guide. Version Q2.21. Quantis, CIRAIG, Center for Risk Science and Communication, Ann Arbor, MI

Humbert S, Marshall J, Shaked S, Spadaro J, Nishioka Y, Preiss P, McKone T, Horvath A, Jolliet O (2011) Intake fraction for particulate matter: recommendations for life cycle impact assessment. Environmental Science & Technology 45 (11):4808-4816

Humphreys D (2010) The great metals boom: A retrospective. Resource Policy 35 (1):1-13

Humphries M (2010) Rare Earth Elements: The Global Supply Chain CRS Report for Congress. Congressional Research Service

Hustrulid WA, Kuchta M (2006) Open pit mining planning and design. 2nd edn. Taylor & Francis, London

ICSG (2012) The World Copper Factbook 2007-2011. International Copper Study Group, Lisbon

IEA (2010) Energy balances of non-OECD countries 2009. International Energy Agency, Paris

IIED and WBCSD (2002) Breaking new ground: Mining, minerals and sustainable development. Final Report on the mining, minerals and sustainable development project (MMSD). International Institute for Envrionment and Development and World Business Council for Sustainable Development, London

ILO (2002) Global report: A future without child labour. Report I(B) International Labour Conference. International Labour Office, Berlin

ILO (2014) International labour standards on forced labour. International Labour Organization. http://ilo.org/global/standards/subjects-covered-by-international-labour-standards/forced-labour/lang--en/index.htm.

Institut für Ökologie e.V. (2008). http://www.oeko.de/service/kea/.

IntierraRMG (2013) Raw materias data. Stockholm

ISO 14040 (2006) Environmental management - Life cycle assessment - Principles and framework. ISO 14040:2006. European Committee for Standardisation, Brussels

ISO 14044 (2006) Environmental management - Life cycle assessment - Requirements and guidelines. ISO 14040:2006. European Committee for Standardisation, Brussels

JLCA (2012) LIME2 - Life cycle impact assessment method based on endpoint modeling. JLCA News Letter No. 14. LCA Society of Japan, Tokyo

Jolliet O, Margni M, Charles R, Humbert S, Payet J, REbitzer G, Rosenbaum R (2003) IMPACT 2002+: a new life cycle impact assessment methodology. International Journal of Life Cycle Assessment 8 (6):324-330

Jolliet O, Müller-Wenk R, Bare J, Brent A, Goedkoop M, Heijungs R, Itsubo N, Pena C, Pennington D, Potting J, Rebitzer G, Stewart M, Haes HUd, Weidema B (2004) The LCIA midpoint-damage framework of the UNEP/SETAC Life Cylce Initiative. International Journal of Life Cycle Assessment 9 (6):394-404

Jørgensen A (2012) Social LCA - a way ahead? International Journal of Life Cycle Assessment 18 (2):296-299

Jørgensen A, Bocq A, Nazarkina A, Hauschild M (2008) Methodologies for social life cycle assessment. International Journal of Life Cycle Assessment 13 (2):96-103

Jørgensen A, Hermann IT, Birk Mortensen J (2010a) Is LCC relevant in a sustianability assessment? International Journal of Life Cycle Assessment 15 (6):531-532

Jørgensen A, Herrmann IT, Bjorn A (2013) Analysis of the link between a definition of sustainability and the life cycle methodologies. International Journal of Life Cycle Assessment 18 (8):1440-1449

Jørgensen A, Lai LCH, Hauschild MZ (2010b) Assessing the validity of impact pathways for child labour and well-being in social life cycle asessment. International Journal of Life Cycle Assessment 15 (1):5-16

Jørgensen SV, Hauschild MZ, Nielsen PH (2014) Assessment of urgent impacts of greenhouse gas emissions - the climate tipping potential (CTP). International Journal of Life Cycle Assessment 19 (4):919-930

Kaminska I (2009) Forget treasuries, is copper the future for China. Financial Times, 16. April 2009

Kannan S (2014) Child labour: India's hidden shame. BBC, 5. February 2014

Kapur A, Graedel TE (2006) Copper mines above and below the ground. Environmental Science & Technology 40 (10):3135-3141

Kaufman RJ (1970) Life cycle costing: A decision-making tool for capital equipment acquisition. Cost Management 2 (March-April):21-28

Kerkow U, Martens J, Müller A (2012) Vom Erz zum Auto - Abbaubedingungen und Lieferketten im Rohstoffsektor und die Verantwortung der deutschen Automobilindustrie. MISEREOR e.V., "Brot für die Welt", Global Policy Forum, Aachen, Bonn, Stuttgart

Kesler SE (1994) Mineral resources, economics and the environment. Macmillan College Publishing Company, New York

Kesler SE (2007) Mineral supply and demand into the 21st century. U. S. Geological Survey, Reston

Kleijn R (2012) Materials and energy: a story of linkages. Leiden University, Leiden

Klinglmair M, Sala S, Brandao M (2013) Assessing resource depletion in LCA: a review of methods and methodological issues. International Journal of Life Cycle Assessment 19 (3):580-592

Klöpffer W (2008) Life cycle sustainability assessment of products. International Journal of Life Cycle Assessment 13 (2):89-95

Klöpffer W, Ciroth A (2011) Is LCC relveant in a sustainability assessment. International Journal of Life Cycle Assessment 16 (6):99-101

Koellner T, Baan Ld, Beck T, Brandão M, Civit B, Margni M, Canals LMi, Saad R, Souza DMd, Müller-Wenk R (2013) UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. International Journal of Life Cycle Assessment. doi:10.1007/s11367-013-0579-z

Krausmann F, Gingrich S, Eisenmenger N, Erb K-H, Haberl H, Fischer-Kowalski M (2009) Growth in global materials use, GDP and population during the 20th century. Ecological Economics 68 (10):2696-2705

Krautkraemer JA (2005) Economics of natural resource scarcity: the state of the debate. Discussion Paper 05-14. Resources for the Future, Washington, DC

Lindeijer EW, Müller-Wenk R, Steen B (2002) Impact assessment of resources and land use. In: Udo de Haes HA, Finnveden G, Goedkoop M et al. (eds) Life-cylce impact assessment: striving towards best practice. Published by the Society of Environmental Toxicology and Chemistry (SETAC), Pensacola, FL, pp 11-64

Liu S, Cai L, Li Z (2012) Social responsibilities and evaluation indicators of listed companies in the perspective of interest groups. American Journal of Industrial and Business Management 2 (3):102-107

Malthus TR (1798) An essay on the principle of population, as it affects the future improvement of society with remarks on the speculations of Mr. Godwin, M. Condorcet and other writers. J. Johnson, London

Mancini L, De Camillis C, Pennington D (eds) (2013) Security of supply and scarcity of raw materials. Publications Office of the European Union, Luxemburg

Martínez-Blanco J, Lehmann A, Munoz P, Antón A, Traverso M, Rieradevall J, Finkbeiner M (2014) Application challenges for the socal LCA of fertilizers within life cycle sustainability assessment. Journal of Cleaner Production 69:34-48

Meadows D, Randers J, Meadows D (2004) Limits to growth - The 30-year update. Chelsea Green Publishing Company, Vermont

Meadows DH, Meadows DL, Randers J, Behrens WW (1972) The limits to growth. A report of the Club of Rome. Universe Books, New York

Meijer A, Huijbregts M, Hertwich E, Reijnders L (2006) Including human health damages due to road traffic in life cycle assessment of dwellings. International Journal of Life Cycle Assessment 11 (1):64-71

MEND (2009) Environmental code of practice for metal mines. Ministry of Environment, Ottawa, Ontario

Mikesell RF (1994) Sustainable development and mineral resources. Resource Policy 20 (2):83-86

Milà i Canals L (2003) Contribution to LCA methodology for agricultural systems. Site-dependency and soil degradation impact assessment., Universitat Autónoma de Barcelona,

Milà i Canals L (2007) Land Use in LCA: A New Subject Area and Call for Papers. International Journal of Life Cycle Assessment 12 (1 Editorial)

Milà i Canals L, Bauer C, Depestele J, Dubeuil A, Knuchel R, Gaillard G, Michelsen O, Mueller-Wenk R, Rydgren B (2007) Key elements in a framework for land use impact assessment within LCA. International Journal of Life Cycle Assessment 12 (1):5–15

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being biodiversity synthesis. World Resources Institute, Washington, DC

Mirovalev M, Kramer AE (2013) In Uzbekistan, the practice of forced labor lives on during the cotton harvest. NY Times, 17.12.2013

Misra KC (2000) Understanding mineral deposits. Kluwer Academic Publishers, Dordrecht

Moll S, Bringezu S, Schütz H (2003) Resourc use in Europen countries. An estimate of materials and waste streams in the European Community including imports and exports, using the instrument of material flow analysis. European Topic Centre on Waste and Material Flows, Copenhagen

Moon CJ, Evans AM (2006) Ore, mineral economics, and mineral exploration. In: Moon CJ, Whateley MKG, Evans AM (eds) Introduction to mineral exploration. Blackwell Publishing Ltd, Oxford, UK, pp 1-18

Morrison D (2006) Driving mining underground. Engineering & Mining Journal 207 (5):60

Moss RL, Tzimas E, Kara H, Willis P, Kooroshy J (2011) Critical metals in strategic energy technologies. JRC Scientific and Technial Reports, EUR 24884 EN. European Commission Joint Research Centre, Brussels

Mudd GM (2009) The sustainability of mining in Australia - key production trends and their environmnetal implications for the future. Research Report RR5. Monash University and the Mineral Policy Institute Melbourne

Mudd GM (2010) The environmental sustainability of mining in Australia: key mega-trends and looming constraints. Resource Policy 35 (2):98-115

Müller-Wenk R (1978) Die ökologische Buchhaltung: Ein Informations- und Steuerungsinstrument für umweltkonforme Unternehmenspolitik. Campus Verlag, Frankfurt

Müller-Wenk R (1999) Depletion of abiotic resources weighted on base of 'virtual' impacts of lower grade deposits used in the future. IWÖ-Diskussionsbeitrag nr. 57. St. Gallen

Nagurney A (2006) Supply chain network economics: Dynamics of prices, flows, and profits. Edward Elgar Publishing, Northampton, MA

Nassar NT, Barr R, Browning M, Diao Z, Fiedlander E, Harper EB, Henly C, Kavlak G, Kwatra S, Jun C, Warren S, Yang M-Y, Graedel TE (2012) Criticality of the Geological Copper Family. Environmental Science & Technology 46 (2):1071-1078

National Research Council (2008) Minerals, Critical Minerals, and the U.S. Economy. National Academies Press, Washington, DC

Norgaard RB, Leu GJ (1986) Petroleum accessibility and drilling technology: An analysis of US development costs from 1959 to 1978. Land Economics 62 (1):14-25

Norgate T, Haque N (2010) Energy and greenhouse gas impacts of mining and mineral processing operations. Journal of Cleaner Production 18 (3):266-274

Norgate TE, Jahanshahi S, Rankin WJ (2007) Assessing the environmental impact of metal production processes. Journal of Cleaner Production 15 (8-9):838-848

Social Hotspot Database (2014) http://socialhotspot.org/.

Notman A (1935) Estimated world reserves of copper. Copper resources of the world. The 16th International Geological Congress, Washington, DC

Nuccitelli D (2011) What tar sands and the Keystone XL pipeline mean for climate change. The Guardian, 23. August 2011

Nunez C (2014) Boycotting tar sands oil: will it work? National Geographic, 5. May, 2014,

Nuss P, Harper EM, Nassar NT, Reck BK, Graedel TE (2014) Criticality of iron and its principle alloying elements. Environmental Science & Technology 48 (7):4171-4177

Oryx Stainless (2012) Key raw materials nickel, chrome and iron: Limited availabiilty despite sufficient geological reserves. Oryx Stainless Group, Mühlheim an der Ruhr/Dordrecht

PE International (2013) GaBi 6 Software-System and Database for Life Cycle Engineering. Stuttgart, Echterdingen

Pennington DW, Potting J, Finnveden G, Lindeijer E, Jolliet O, Rydberg T, Rebitzer G (2004) Life cycle assessment part 2: current impact assessment practice. Environment International 30 (5):721-739

Petersen U, Maxwell RS (1979) Historical mineral production and price trends. Mining Engineering 31:25-34

Petrie J (2007) New models of sustainability for the resources sector - a focus on minerals and metals. Trans IChemE, Part B, Process Safety and Environmental Protection 85 (B1):88-98

Pope C, Burnett R, Krewski D, Jerrett M, Shi Y, Calle E, Thun M (2009) Cardiovascular mortality and exposure to airborne fine particulate matter and cigarette smoke - shape of the exposure-response relationship. Circulation 120 (11):941-948

Prior T, Giurco D, Mudd G, Mason L, Behrisch J (2012) Resource depletion, peak minerals and the implications for sustainable resource management. Global Environmental Change 22 (3):577-587

Radetzki M (2002) Is resource depleiton a trheat to human progress? Oil and other critical exhaustible materials. Paper presented at the energex'2002, Cracow, 19-24 May

Rankin WJ (2011) Minerals, metals and sustainability: meeting future material needs. CSIRO Publishing, Collingwood

Reap J, Roman F, Duncan S, Bras B (2008) A survey of unresolved problems in life cycle assessment, Part 2: impact assessment and interpretation. International Journal of Life Cycle Assessment 13 (5):374-388

Reimann K, Finkbeiner M, Horvath A, Matsuno Y (2010) Evaluation of environmental life cycle approaches for policy and decision making support in micro and macro level applications. JRC Scientific and Technical Reports. Europen Commission, Joint Research Centre, Institute for Environment and Sustainability, Ispra

Reuter MA, Heiskanen K, Boin U, Schaik Av, Verhoef E, Yang Y, Georgalli G (2005) The Metrics of Material and Metal Ecology. Developments in Mineral Processing 16. Elsevier, Amsterdam

Reynolds DB (1999) The mineral economy: how prices and costs can falsly signal decreasing scarcity. Ecological Economics 31 (1):155-166

Ricardo D (1821) On the principles of plitical economy and taxation. John Murray, London

Ritthoff M, Rohn H, Liedtke C (2002) Calculating MIPS - resource productivity of products and services. Wuppertal Spezial 27e. Wuppertal Institut for Climate, Environment and Energy, Wuppertal

Rosenau-Tornow D, Buchholz P, Riemann A, Wagner M (2009) Assessing the long-term supply risks for mineral raw materials - a combined evaluation of past and future trends. Resource Policy 34 (4):161-175

Rosenbaum R, Bachmann T, Swirsky Gold L, Huijbregts M, Larsen H, MacLeod M, Margni M, McKone T, Payet J, Schuhmacher M, van de Meent D, Hauschild M (2008) USEtox - the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshawater ecotoxicity in life cycle impact assessment. International Journal of Life Cycle Assessment 13 (7):532-546

Rungi A (2010) From export dependency to dynamic comparative advantages. POLINARES working paper no. 10.

Sala S, Farioli F, Zamagni A (2013) Progress in sustainability science: lessons learnt from current methodologies for sustainability assessment: Part 1. International Journal of Life Cycle Assessment 18 (9):1653-1672

SAMREC (2000) South African code for reporting mineral resources and mineral reserves. South African Mineral Resource Committee (SAMREC), South African Institute of Mining and Metallurgy, Johannesburg

Schenck RC (2001) Land use and biodiversity indicators for life cycle impact assessment. International Journal of Life Cycle Assessment 6 (2):114–117

Schneider L, Berger M, Finkbeiner M (2011) Economic material availability as a new area of protection for life cycle sustainability assessment. Paper presented at the SETAC Europe 21st Annual Meeting, Milano, 15-19 May

Science and Technology Committee (2011) Strategically important metals. Fifth report of session 2010-12. House of Commons, London

SHDB (2014) Social Hotspot Database. www.socialhotspot.org

Shedd KB (2013) Minerals Yearbook: Cobalt. U.S. Geological Survey, Department of the Interior, Washington, DC

Shen L, Cheng S, Gunson AJ, Wan H (2005) Urbanization, sustainability and the utilization of energy and mineral resources in China. Cities 22 (4):287-302

Sievers H (2012) Geological Availability. POLINARES working paper n. 17. POLINARES - EU policy on natural resources, Brussels

Simon J (1998) The Ultimate Resource 2. Princeton University Press, Princeton

Simon JL (1980) Resources, population, environment: an oversupply of false bad news. Science 208 (4451):1431-1437

Skinner BJ (1976) A second iron age ahead? American Scientist 64 (3):158-169

Skinner BJ (1979) Earth resources. Proceedings of the national Academy of Sciences 76 (9):4121-4217

Skinner BJ (2001) Exploring the resources base. Paper presented at the Workshop on "The long-run availability of minerals", Washington, DC, 22-23 April

Solomon F, Katz E, Lovel R (2008) Social dimensions of mining: Research, policy and practice challenges for the minerals industry in Australia. Resource Policy 33 (3):142-149

Souza D, Flynn D, de Clerck F, Rosenbaum R, de Melo Lisboa H, Koellner T (2013) Land use impacts on biodiversity in LCA: proposal of characterization factors based on functional diversity. International Journal of Life Cycle Assessment DOI 10.1007/s11367-013-0578-0

Spiegel Online (2013) Kinderarbeit und Umweltverschmutzung: Norwegens Staatsfonds zieht Geld aus Unternehmen ab. Spiegel Online

Stamp A, Lang DJ, Wäger PA (2012) Environmental impacst of a transition toward e-mobility: the present and future role of lithium carbonate production. Journal of Cleaner Production 23 (1):104-112

Steen B (1999) A systematic approach to environmental priority strategies in product development (EPS). Version 2000 - models and data. Report 1999:5. Chalmers University of Technology, Centre for Environmental Assessment of Products and material Systems, Gothenburg

Steen B, Borg G (2002) An estimation of the cost of sustainable production of metal concentrates from the Earth's crust. Ecological Economics 42 (3):401-413

Steen BA (2006) Abiotic resource depletion - different perceptions of the problem with mineral deposits. International Journal of Life Cycle Assessment 11 (1):49-54

Steinbach V, Wellmer F-W (2010) Consumption and use of non-renewable mineral and energy raw materials from an economic geology point of view. Sustainability 2 (5):1408-1430

Steinberger JK, Krausmann F, Eisenmenger N (2010) Global patterns of materials use: A socioeconomic and geophysical analysis. Ecological Economics 69 (5):1148-1158

Stewart M, Weidema B (2005) A consisten framework for assessing the impacts from resource use, a focus on resource functionaility. International Journal of Life Cycle Assessment 10 (4):240-247

Swart P, Dewulf J (2013) Quantifying the impacts of primary metal resource use in life cycle assessment based on recent mining data. Resources, Conservation and Recycling 73:180-187

Talens Peiró L, Villalba Méndez G, Ayres RU (2013) Material flow analysis of scarce metals: Sources, functions, end-uses and aspects for future supply. Environmental Science & Technology 47 (6):2939-2947

Teevs C (2010) Kinderarbeit in Afrika: Bittere Ernte. Spiegel online, 06.10.2010

The World Bank (2014) Global Economic Prospects. The World Bank, Washington DC

The World Bank Group (2012) Worldwide Governance Indicators.

Tilton JE (1996) Exhaustible resources and sustainable development - two different paradigms. Resource Policy 22 (1/2):91-97

Tilton JE (2003) On borrowed time? Assessing the threat of mineral depletion. Resources for the Future, Washington, DC

Tilton JE, Lagos G (2007) Assessing the long-run availability of copper. Resources Policy 32 (1-2):19-23

Tsurukawa N, Prakash S, Manhart A (2011) Social impact of artisanal cobalt mining in Katanga, Democratic Republic of Congo. Öko-Institut e.V., Freiburg

Turner G (2008) A comparison of the limits to growth with thirty years of reality. CSIRO Sustainable Ecosystems, Canberra

U.S. Bureau of Mines (1960) Mineral facts and problems. Bulletin - Bueau of Mines. U.S. Govt. Print Off. , Washington, DC

U.S. Bureau of Mines (1975) Mineral facts and problems. Bulletin - Bueau of Mines. U.S. Govt. Print Off. , Washington, DC

Udo de Haes H, Lindeijer E (2002) The conceptural structure of lify-cylce impact assessment. In: Udo de Haes HA, Finnveden G, Goedkoop M et al. (eds) Life-cycle impact assessment: Striving towards best practice. Published by the Society of Environmental Toxicology and Chemistry (SETAC), Pensacola, pp 209-226

Udo de Haes HA, Finnveden G, Goedkoop M, Hauschild M, Hertwich EG, Hofstetter P, Jolliet O, Klöpffer W, Krewitt W, Lindeijer EW, Mueller-Wenk R, Olson SI, Pennington DW, Potting J, Steen B (2002) Life cycle impact assessment: Striving towards best practice. Published by the Society of Environmental Toxicology and Chemistry (SETAC), Pensacola

UNDP (2011) Human Development Report 2011 -Sustainability and Equity: A Better Future for All. New York

UNEP (2010a) Assessing the Environmental Impacts of Consumption and Production; Priority Products and Materials. A Report of the Working Group on the Environmental Impacts of Products and Materials to the International Panel for Sustainable Resource Management. Hertwich, E., van der Voet, E., Suh, S., Tukker, A., Huijbregts M., Kazmierczyk, P., Lenzen, M., McNeely, J., Moriguchi, Y., Paris

UNEP (2010b) Metal stocks in society. United Nations Environment Programme, International Panel for Sustainable Resource Management, Paris

UNEP (2010c) United Nations Environment Programme (UNEP): connecting the dots - Biodiversity, adaptation, food security and livelihoods United Nations Environment Programme

UNEP (2011a) Decoupling natural resource use and environmental impacts from economic growht. A report of the working group on decoupling to the International Resource Panel. United Nations Environment Programme, Paris

UNEP (2011b) Estimating long-run geological stocks of metals. Working Paper, April 6, 2011. UNEP International Panel on Sustainable Resource Management, Working Group on Geological Stocks of Metals, Paris

UNEP (2011c) Recycling Rates of Metals - A Status Report. United Nations Environmental Programme, International Resources Panel, Paris

UNEP (2011d) Towards a life cycle sustainability assessment. United Nations Environment Programme, UNEP/SETAC Life Cycle Initiative, Paris

UNEP (2012) Global Environment Outlook 5. United Nations Environment Programme, Nairobi

UNEP (2013) Environmental risks and challenges of anthropogenic metals flows and cycles. A Report of the Working Group on the Global Metal Flows to the International Resource Panel. van der Voet, E.; Salminen, R.; Eckelman, M.; Mudd, G.; Norgate, T.; Hischier, R. United Nations Environment Programme, Paris

UNEP/ SETAC (2009) Guidelines for social life cycle assessment of products. UNEP/SETAC Life Cycle Initiative at UNEP, CIRAIG, FAQDD and the Belgium Federal Public Planning Service Sustainable Development, Paris

UNEP/ SETAC (2013) The methodological sheets for sub-categories in social life cycle assessment. United Nations Environment Programme and SETAC Life Cycle Initiative, Paris

UNFPA (2012) Population matters for sustainable development. The United Nations Population Fund, New York

United Nations (1987) Our common future. Report of the World Commission on Environment and Development. Oxford University Press, Oxford

United Nations (2011) World population prospects: The 2010 revisions. United Nations, Department of Economic and Social Affairs, Population Division, New York

United Nations (2013) Population and vital statistics report. Statistical papers, Series A Vol. LXV. United Nations, Department of Economic and Social Affairs, Statistics Division, New York

USEtox (2013) USEtox model (version 1.10 beta).

USGS (2010a) Historical Statistics for Mineral and Material Commodieties in the United States. U.S. Geological Survey, Washington, DC

USGS (2010b) Mineral Commodity Summaries. U.S. Geological Survey, Washington, D.C., USA

USGS (2013) Minerals Yearbook. Vol I: Metals and minerals. U.S. Geological Survey, Washington, DC

USGS (2014a) Mineral commodity summaries. U.S. Geological Survey, Department of the Interior, Reston

USGS (2014b) Mineral commodity summaries 2014 - Appendix C. U.S. Geological Survey, U.S. Department of the Interior, Washington, DC

Valero A, Valero A (2009) The crepuscular planet. Part II: A model for the exhaused continental crust. Paper presented at the ECOS, Paraná, 31 August- 3 September

Valero A, Valero A, Amaya M (2009) Inventory of the exergy resource on earth including its minral capital. Energy 35 (2):989-995

Valero A, Valero A, Domínguez A (2013) Exergy replacement cost of mineral resources. Journal of Environmental Accounting and Managment 1 (2):147-158

van Kempen EEMM, Kruize H, Boshuizen HC, Ameling CB, Staatsen BAM, de Hollander AEM (2002) The association between noise exposure and blood pressure and ischemic heart disease: a meta-analysis. Environmental Health Perspectives 110 (3):307–317

van Oers L, deKoning A, Guinée J, Huppes G (2002) Abiotic Resource Depleiton in LCA. Road and Hydraulic Engineering Institute, Leiden

VDI (2013) http://www.vdi.de/technik/fachthemen/energie-und-umwelt/fachbereiche/ressourcenmanagement/ themen/richtlinienwerk-zur-ressourceneffizienz-zre/.

Verhoef EV (2004) The ecology of metals. Delft University of Technology, Delft

Vieira M, Ponsionen TC, Goedkoop M, Huijbregts MAJ (2011) Mineral and fossil resources. Development and application of environmental life cycle impact assessment methods for improved sustainability characterisation of technologies (LC-IMPACT). Seventh Framework Programme, European Union, Brussels

Vieira MDM, Goedkoop MJ, Storm P, Huijbregts MAJ (2012) Ore grade decrease as life cycle impact indicator for metal scarcity: the case of copper. Environmental Science & Technology 46 (23):12772-12778

von der Lippe P (1993) Deskriptive Statistik. Gustav Fischer Verlag, Stuttgart

Wadia C, Albertus P, Srinivasan V (2011) Resource constraints on the battery energy storage potential for grid and transportation applications. Journal of Power Sources 196 (3):1593-1598

Wäger P, Classen M (2006) Metal availability and supply: the many facets of scarcity. Paper presented at the 1st International Symposium on Material, Minerals, & Metal Ecology, Cape Town, South Africa, 14-15 November

Wäger PA, Widmer R, Stamp A (2011) Scarce technology metals - applications, criticalities and intervention options. Federal Office for the Environment (FOEN), Bern

Wagner LA (2002) Materials in the economy - Material flows, scarcity, and the environment. U.S. Geological Survey Circular 1221. U.S. Geological Survey, U.S. Department of the Interior, Denver, CO

Watson RT, Rosswall T, Steiner A, Töpfer K, Arico S, Bridgewater P Ecosystems and human well-being: biodiversity sysnthesis. In: Watson RT, Rosswall T, Steiner A, Töpfer K, Arico S, Bridgewater P (eds) Ecosystems, Washington, 2005. World Resources Institute. doi:10.1196/annals.1439.003

WCED (1987) Our common future. World Commission on Environment and Development, Oxford University Press, Oxford

Wehmeier S, McIntosh C, Turnbull J, Ashby M (2005) Oxford Advances Learner's Dictionary, vol 7. Oxford University Press, Oxford

Weidema B, Finnveden G, Stewart M (2005) Impacts from resource use - a common position paper. International Journal of Life Cycle Assessment 10 (6):382

Wellmer F-W, Becker-Platen JD (2002) Sustainable development and the exploitation of mineral and energy resources: a review. International Journal of Earth Sciences 91 (5):723-745

Wernick IK (1996) Consuming materials: The American way. Technological Forecasting and Social Changes 53 (1):111-122

Weterings R, Bastein T, Tukker A, Rademaker M, Ridder Md (2013) Resources for our future - key issues and best practices in resource efficiency. The Hague Centre for Strategic Studies (HCSS) and TNO, Amsterdam

Wolfensberger M, Lang DJ, Scholz RW (2007) (Re-) structuring the filed of non-energy mineral resource scarcity. Working Paper 43. ETH Zürich, Zürich

World Economic Forum (2012) The Global Enabling Trade Report 2012 - Reducing Supply Chain Barriers. World Economic Forum, Geneva

Yaksic A, Tilton JE (2009) Using the cumulative availability curve to assess the threat of mineral depletion: The case of lithium. Resources Policy 34 (4):185-194

Yellishetty M, Mudd GM, Ranjith PG (2011) The steel industry, abiotic resource depletion and life cycle assessment: a real or perceived issue? Journal of Cleaner Production 19 (1):78-90

Yellishetty M, Ranjith PG, Tharumarajah A, Bhosale S (2009) Life cycle assessment in the minerals and metals sector: a critical reveiw of selected issues and challenges. International Journal of Life Cycle Assessment 14 (3):257-267

Zacune J (2013) Lithium. GLOBAL 2000 Verlagsges. m.b.H., Vienna

Zinc for Life (2013) Zinc Environmental Profile. www.zincforlife.org. Accessed 8. January 2014

Zwartendyk J, Abelson PH, Baumann HG, Clark JP, Dalheimer M, Darmstadter J, Demeny P, Gordon RL, Harris DP, Krupp H-J, Tilton JE, Wiedenbein FW (1987) Human factors influencing resource availability and use. In: McLaren DJ, Skinner BJ (eds) Resources and world development. Dahlem Workshop Reports. John Wiley & Sons Limited, Dahlem, pp 508-523

GLOSSARY

Abiotic resources	Outside the biosphere – stock reduction has no direct influence on ecosystems (Lindeijer et al. 2002).
Alloy	A mixture of two or more elements (Rankin 2011).
Area or protection	A cluster of category endpoints of recognizable value to society (Udo de Haes and Lindeijer 2002).
Availability	The physical existence and accessibility of abiotic resources.
Biotic resources	Biotic resources are alive, at least to the moment of extraction. Biotic stocks to show replenishment rates (Lindeijer et al. 2002).
Characterization	Calculation of the extent of environmental impact per category (Baumann and Tillman 2004).
Characterization factor	Factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator (ISO 14044 2006).
Companion metal	Metals that are closely connected to certain major metal deposits and which mine production depends heavily on the host metals (Hagelüken and Meskers 2010).
Country concentration	The global distribution of production of a mineral commodity among countries, measured by a country concentration ratio according to the Herfindahl-Hirschman Index (HHI).
Depletion	Process of gradually using up nature's endowment of mineral deposits (Lindeijer et al. 2002; Zwartendyk et al. 1987).
Depletion time	Time that economic reserves will last based on current production. Also referred to as reserve-to-production ratio.
Deposit	A defined or partially defined body of mineralization which may become an ore, depending on economic conditions.
Effective scarcity	A shortage in supply of a mineral relative to the interests and needs (demands) of humans today.
Endpoint	Those elements of an environmental mechanism that are themselves of value to society (Udo de Haes and Lindeijer 2002).
Endpoint indicator	Indicator expressing an impact at the end of a cause-effect-chain.
Extractable global resource	The quantity of a given resource that is judged to be worthy of extraction over the long term given anticipated improvements in exploration and technology (UNEP 2011b).
Functional unit	Reference flow to which all other flows in the evaluation are related (Baumann and Tillman 2004). Unit of comparison in comparative studies (1kg of metal).
Grade	The percentage of rock composed of valuable material.

Host metal	Metals that are mined for themselves.
Human welfare/wellbeing	Welfare and wellbeing refer to an overall condition, emphasizing happiness and contentment, including one's standard of living in financial and material ways.
Impact category	Impact categories are logical groupings of results, related to environmental, economic or social issues of interest.
Life cycle	Consecutive and interlinked stages of the product system, from raw material acquisition or generation from natural resource to final disposal (ISO 14044 2006).
Life cycle assessment (LCA):	Assessment technique that aims at addressing the potential environmental impacts of products and production processes throughout the entire life cycle (ISO 14044 2006).
Life cycle impact assessment	Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle (ISO 14044 2006).
Life cycle inventory (LCI)	Compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO 14044 2006).
Life cycle sustainability assessment (LCSA)	LCSA provides a framework for the comprehensive evaluation of economic and social impacts of products, in addition to environmental ones (Finkbeiner et al. 2010; Klöpffer 2008; UNEP 2011d).
Material	Substances which are used by humans to create goods (Rankin 2011).
Material inventory	Collection of all relevant materials included in the product system.
Midpoint	Midpoints concern all elements in an environmental mechanism of an impact category that fall between environmental intervention and endpoint (Udo de Haes and Lindeijer 2002).
Midpoint indicator	Indicator expressing an impact in the middle of a cause-effect chain.
Mineralogical barrier	*The mineralogical barrier* separates the smaller amount of minerals at higher concentrations and in easily accessible form (*deposits*) from the larger amount of a metal at lower concentrations in more tightly bound form (Skinner 1979).
Natural resource stock	The in situ amount of resources in the ground.
Non-renewable resources	Resources which cannot be regenerated in human lifetimes.
Normalization	Relation to a reference value. Impact of the studied material is related to the total environmental impact in a region so the relative contribution can be determined (Baumann and Tillman 2004).
Ore	Rock that can be mined for its mineral content at a profit.
Physical scarcity	Scarcity resulting from the depletion of resources.

Product system	Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product (ISO 14044 2006).
Raw materials	Materials in their natural, unprocessed or minimally processed state (e.g., iron ore).
Reserve	Reserves measure the metal content in deposits that are known and profitable to exploit at current prices, state of technology, etc. (Tilton and Lagos 2007; USGS 2014b).
Reserve base	That part of a resource that meets specified minimum physical and chemical criteria related to current mining and production practices (UNEP 2011b; USGS 2014b).
Reserve-to-production ratio	See 'depletion time'.
Resource	A concentration of naturally occurring minerals in or on the earth's crust in such form and amount that economic extraction is currently or potentially feasible (USGS 2014b).
Resource scarcity	Situation whereby a decline in availability or accessibility occurs relative to the demand of a resource.
Social life cycle assessment (SLCA)	Social impact assessment technique that aims to assess the social aspects of products and their negative (and positive) along their life cycle (UNEP/ SETAC 2009).
Social hotspots	Social hotspots are unit processes located in a region where a situation occurs that may be considered as a problem or risk (UNEP/ SETAC 2009).
Social impacts	Social impacts are consequences of positive or negative pressures on social endpoints (i.e., wellbeing) (UNEP/ SETAC 2009).
Stock	Collective amount available of one specific resource/material.
Supply chain	Supply chain refers to activities that transform natural resources, raw materials and components into finished products (Nagurney 2006).
Ultimate reserves	The quantity of resources that is ultimately available in the earth's crust. Estimated by multiplying the average natural concentration of the resources in the earth's crust by the mass or volume of these media (e.g., the mass of the crust assuming a certain depth of for example 10km) (Guinée 1995).

APPENDIX I

The scope of the resource availability assessment is narrowed down to metallic minerals and fossil fuel resources that are retrieved from non-renewable resource stocks, locked below ground and that do not have an obvious functions for delivering ecosystems services. Land, water, solar radiation or soil, which are considered, at least in parts, abiotic and the assessment of depletion or scarcity of biotic resources are not addressed in this work. This is due to different significance of the availability problem. Such differences in the underlying mechanism requires different models and separate metrics for assessment (see also European Commission 2010c). Some of the underlying reasons for this distinction are described in Table A.1.

Table A.1: Differences in the resource mechanism – A classification

Mechanism	Description
Resource classification	Water and land can be included in the category of abiotic resources, but are often seen as resource classes in their own rights and (impact) assessment separate from other abiotic resources is common practice.[1] Thus, the assessment of water and land is excluded in this dissertation.
*Stock propertie*s	Nutrients from soil minerals are *fund* resources that are temporarily or locally depletable but that can be regenerated within human lifetime.[2] Continuous resources (flow resources), such as sunlight and wind, are nondepletable but with a limited availability at a certain time. Contrary natural deposits and stocks of mineral resources are irreversibly depletable and deposits cannot regenerate within human lifetimes as the renewal rate is extremely low. Even though mineral nutrients are considered as abiotic factors, their characteristics differ significantly from abiotic resources that form the basis of the assessment in this dissertation.[3]
Ecosystem service	Resources like copper or oil are not important components of living ecosystems. When assessing resources such as fresh water or soil, the impact assessment, in addition to representing potential scarcity of resources, should also represent the current degradation of biodiversity and of other life supporting functions. Similarly, biotic resources have a role in the maintenance of the life support system and thus have an intrinsic value, other than mineral resources.[4]

[1]see, e.g., Berger et al. (2012), Curran et al. (2011), Henzen et al. (2008), or Pfister et al. (2009) [2]Lindeijer et al. (2002) [3]Mineral nutrients are taken up by the plant from the soil in various ionic forms and do not involve an extraction process induced by humans. These ions are replenished through mineral decomposition and decay of organic matter. [4]Lindeijer et al. (2002)

APPENDIX II

This appendix supplements the discussion in Chapter 3 and highlights the need for a consistent approach for the quantification of geologic resource stocks.

Reliable estimates of the total amount of minerals that may be available for human use are not in place (Graedel et al. 2014). In this dissertation, data from the USGS is used as a basis for determining the geologic stock of resources. The *resource* is currently used as the “best estimate” for the ultimately extractable amount of resources from the earth’s crust. Resource numbers are the most expansive of the geologic stock determinations, but are rarely estimated and are available only for a limited number of materials (UNEP 2011b). The possible extent of mineral *resources* can be inferred from the estimated content of each element in the earth’s crust, or their crustal abundance (Crowson 2011). However, those estimates are only available for a limited number of resources and are continually being revised in the light of technical changes, shifts in prices and costs and new knowledge. As Crowson (2011) pointed out, the land-based resources of *copper* were estimated at 1.6 billion tons in 2000, and at more than 3 billion tons in 2011. The task of quantifying geological resources of metals is complex. Mining companies only prove sufficient ore to justify their investments in extraction and processing facilities rather than analyzing what is ultimately available (Crowson 2011). Even though *resource* numbers can be considered as a first indication of the ultimately extractable amount or certain materials, they are applicable only to a limited degree and further discussion is needed.

A recent publications by the UNEP International Panel on Sustainable Resource Management proposed a way for the estimation of long-run geological stocks of metals and published estimates for the *extractable geologic resources* (EGR) (UNEP 2011b). Similarly, Rankin (2011) proposed a way for assessing crustal resources of minerals and proposed estimates of the *quantity of elements in mineral deposits* (EQD). The different numbers for assessing geologic resource stocks are displayed and compared in Figure A.1 and Figure A.2. In Figure A.1 resource numbers used in this work are compared with the EQD and the EGR. Taking into account the logarithmic scale of the figure, significant differences between the different numbers occur. Resource numbers are generally lower than the EQD and EGR, which is in line with their definition. However, for *chromium* and *lead*, resources are higher than the respective EQD and EGR numbers. For *zinc* all three number are very similar.

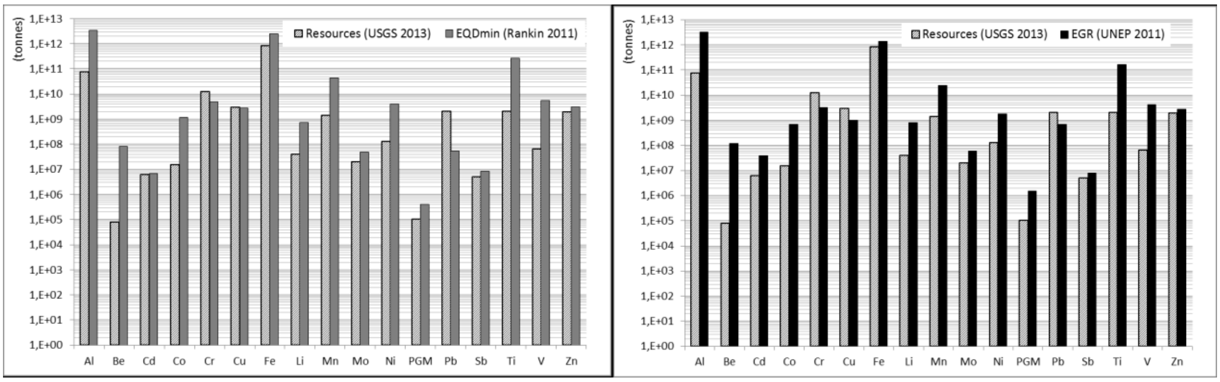

Figure A.1: Overview – *Resources* vs. EQD (left) **and *resources* vs. EGR** (right) **(**based on Rankin 2011, UNEP 2011b, USGS 2013a)

While the EQD and EGR are based on similar assumptions, a high correlation between those factors is expected. This can generally be verified. However, differences occur due to different reference numbers used for determining the crustal abundance and consideration of different depths of the upper continental crust.

To display the significance of the choice of resource number for the results of the assessment of resource depletion, the different characterization models are adapted based on these numbers. In Figure A.2 the ADP and AADP results are displayed, for resources, EGR and EQD respectively. The left bar in the figure represents the $ADP_{\text{ultimate reserves}}$, commonly used as of today. The results of the assessment as displayed in Figure A. highlight the significance of the definition of the resource stocks on the overall results. Different materials dominate the results for the ADP and AADP. Particularly apparent is the high relevance of *lead* for the ADP_{EQD}. This is due to the comparatively small geologic stock identified by means of the EQD (compared to the other numbers, see Figure A.1). Significant differences occur when different reference numbers are used for determining the ultimately extractable amount of resources. For consistent and meaningful results, additional research is needed.

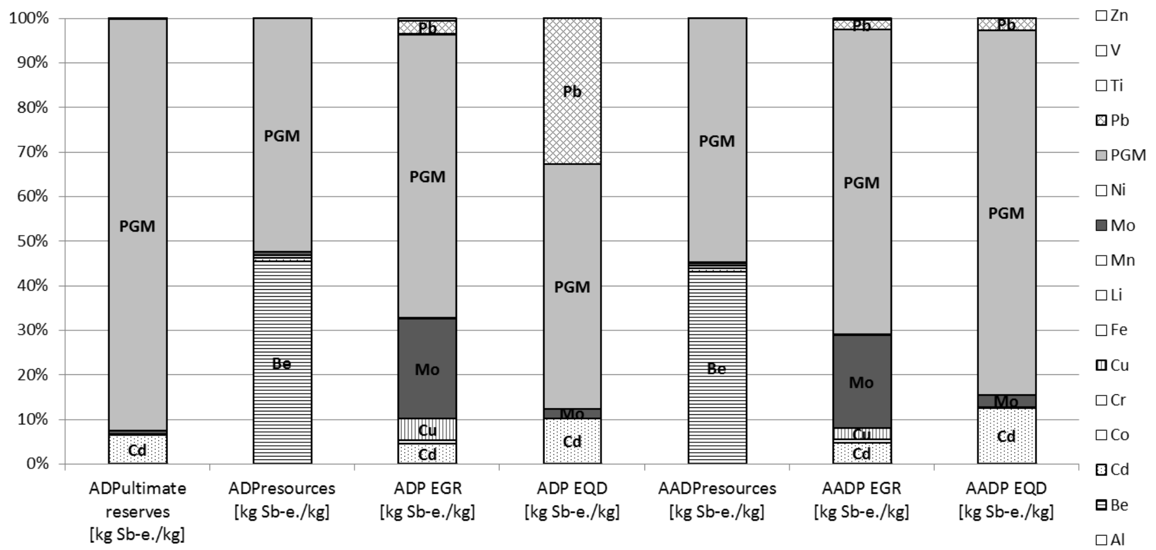

Figure A.2: Overview – ADP and AADP based on different resource numbers

APPENDIX III

This appendix provides relevant background information to the different criteria and indicators evaluated in Chapter 4. In Table A.2 the world reserves and the mine production of the addressed material portfolio are shown.

Table A.2: World reserves and mine production of material portfolio (according to USGS 2014a)

Metal	World reserves [in 1000 tons of metal content]	Mine production [in tons of metal content]	Metal	World reserves [in 1000 tons of metal content]	Mine production [in tons of metal content]
Aluminum (Al)	28,000,000	45,900,000	Molybdenum (Mo)	11,000	259,000
Chromium (Cr)	480,000	25,600,000	Nickel (Ni)	74,000	2,220,000
Cobalt (Co)	7,200	103,000	Platinum Group Metals (PGM)	66	384
Copper (Cu)	690,000	16,900,000	Rare earths oxides	140,000	110,000
Gold (Au)	54	2,690	Silver (Ag)	520	25,500
Iron (Fe)	81,000,000	2,930,000,000	Tin (Sn)	4,700	240,000
Lead (Pb)	89,000	5,170,000	Titanium (Ti)	750,000	13,700,000
Lithium (Li)	13,000	35,000	Zinc (Zn)	250,000	13,500,000
Magnesium (Mg)	2,400,000	6,350,000			

In Table A.3 the companion metal fraction used in this work is displayed. This table supplements Chapter 4.2.3.

Table A.3: Companion metal fraction

Material	Companion metal fraction	Material	Companion metal fraction
Aluminum	0.10	Molybdenum	0.60
Chromium	0.10	Nickel	0.10
Cobalt	0.85	PGM	0.70
Copper	0.10	Rare earths	0.48
Gold	0.12	Silver	0.71
Iron	0.10	Tin	0.10
Lead	0.13	Titanium	0.10
Lithium	0.00	Zinc	0.10
Magnesium	0.10		

(based on data published by Nassar et al. 2012; Nuss et al. 2014; Talens Peiró et al. 2013; USGS 2013)

In Table A.4 the average recycled content for each of the materials in the material portfolio of this dissertation is presented (based on data published by European Commission 2010a; Graedel et al. 2011a; Stamp et al. 2012; UNEP 2011c). This table supplements Chapter 4.2.4.

Table A.4: Recycled content

Material	Recycled content	Material	Recycled content
Aluminum	0.35	Molybdenum	0.17
Chromium	0.13	Nickel	0.32
Cobalt	0.16	PGM	0.35
Copper	0.22	Rare earths	0.01
Gold	0.3	Silver	0.16
Iron	0.22	Tin	0.22
Lead	0.52	Titanium	0.06
Lithium	0	Zinc	0.08
Magnesium	0.14		

In Table A.5, the share of production underlying trade barriers is displayed supplementing Chapter 4.2.7. The trade barriers imposed by the individual countries are weighted by the share of production in the countries.

Table A.5: Trade barriers (according to BDI 2010)

Material	Share of production underlying trade barriers	Material	Share of production underlying trade barriers
Aluminum	0.125	Nickel	0.23
Chromium	0.009	PGM	0.27
Cobalt	0.57	Palladium	0.41
Copper	0.19	Platinum	0.13
Gold	0.13	Rare earths	0.99
Iron	0.21	Silver	0.13
Lead	0.42	Tin	0.38
Lithium	0.12	Titanium	0
Magnesium	0.62	Zinc	0.35
Molybdenum	0.29		

As a supplement to Chapter 4.2.8 the demand growth for the different metals, used as a basis for the determination of the supply risk assessed in this dissertation, is indicated in Table A.6. Data used as a basis for these calculations is retrieved from publicly available and accepted databases or publications.

Table A.6: Demand growth [%]

Material	Annual growth rate [%]	Material	Annual growth rate [%]
Aluminum	5	Molybdenum	5
Chromium	5	Nickel	3.8
Cobalt	2	PGM	4.9
Copper	3	REE	4
Gold	1	Silver	2
Iron	3	Tin	1.8
Lead	3	Titanium	3
Lithium	5	Zinc	3.2
Magnesium	3		

Data based on yearly averages ((Angerer et al. 2009a; BGR 2007; Frondel et al. 2005; Gordon et al. 2006; Hagelüken and Meskers 2010; USGS 2014a)

In Table A.7 the indicator values for the addressed aspects are presented, scaled to a range from 0 to 1 to ease comparability.

Table A.7: Overview data for different indictors and metals used as a basis in this work

	Indicator	Unit	Al	Cr	Co	Cu	Au	Fe	Pb	Li	Mg	Mo	Ni
Depletion time	Reserves	Mt	28.000	480	7.2	680	54 kt	81.000	89	13	2.400	11	74
	Production	Mt	259	25.6	103 kt	16.9	2.6 kt	2930	5.17	35 kt	6.35	259 kt	2.22
	Reserve-to-production ratio	years	108	19	70	41	20	28	17	371	378	42	33
Secondary metal	Recycled content	%	0.35	0.13	0.16	0.22	0.3	0.22	0.52	0	0.35	0.34	0.32
	New material content	%	0.65	0.87	0.84	0.78	0.7	0.78	0.48	1	0.65	0.66	0.68
Country concentration reserves			0.14	0.41	0.24	0.14	0.07	0.13	0.2	0.42	0.16	0.26	0.13
Country concentration production			0.2	0.25	0.32	0.14	0.06	0.20	0.25	0.30	0.53	0.25	0.10
Company concentration production			0.09	0.11	0.02	0.04	0.04	0.06	0.03	0.12	0.02	0.08	0.09
Governance stability	WGI		0.52	0.50	0.71	0.43	0.48	0.50	0.52	0.35	0.60	0.48	0.49
Trade barriers		%	12	0.9	57	19	13	21	42	12	45	27	23
Demand growth		%	5	5	2	3.1	3	3	3	5	2	3	3.8
Companion metal fraction		%	10	10	85	10	12	10	12	0	10	55	10
Socio-economic stability	HDI		0.25	0.37	0.39	0.23	0.26	0.26	0.25	0.17	0.29	0.23	0.29

	Indicator	Unit	PGM	Rare earths	Ag	Sn	Ti	Zn
Depletion time	Reserves	Mt	66 kt	140	520 kt	4.7	750	250
	Production	Mt	384 t	110 kt	25.5 kt	240 kt	7.23	13.5
	Reserve-to-production ratio	years	171	1272	20	20	104	19
Secondary metal	Recycled content	%	0.35	0.01	0.16	0.22	0.06	0.08
	New material content	%	0.65	0.99	0.84	0.78	0.94	0.92
Country concentration reserves			0.91	0.3	0.13	0.17	0.15	0.16
Country concentration production			0.39	0.90	0.13	0.29	0.11	0.15
Company concentration production			0.90	0.903	0.02	0.07	0.13	0.15
Governance stability	WGI		0.49	0.63	0.49	0.60	0.42	0.50
Trade barriers		%	27	99	13	38	0	35
Demand growth		%	5	4	4	1.8	3	3.2
Companion metal fraction		%	70	48	71	10	10	10
Socio-economic stability	HDI		0.33	0.31	0.23	0.32	0.26	0.24

To enable a qualitative comparison the divergence of the indicator values from the threshold value in relation to the maximum possible value across all impact categories was evaluated. In Figure A.3 the divergence of the different materials from the determine threshold (target) is displayed (supplementing Table 4.5 in Chapter 4. 3). For that purpose levels were introduce at 100% and 200% that mark the transition from low risk materials to medium risk materials and medium risk materials to high risk materials. In this regard, materials that exceed the thresholds significantly more than twice are associated with high supply risks.

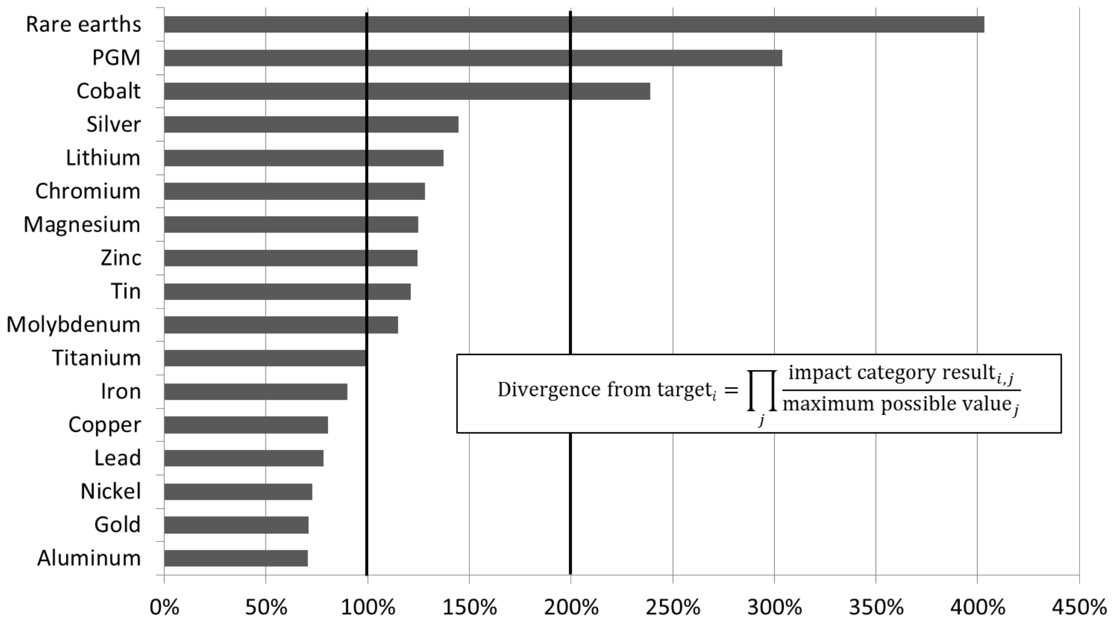

Figure A.3: Divergence from target – Background data for a qualitative comparison

APPENDIX IV

In Table A.8 the ranking of category indicator results for the addressed material portfolio are presented (supplementing Chapter 5.3).

Table A.8: Category indicators results – AP and GWP

CML Acidification Potential [kg SO_2-e.]		**CML Global Warming Potential [kg CO_2-e.]**	
Gold	671.7	Gold	62798
Platinum	259.7	Platinum	13839
Palladium	211.5	Palladium	10090
Ytterbium	14.4	Terbium	1080
Terbium	7.9	Ytterbium	900
Silver	7.5	Silver	300
Samarium	0.9	Samarium	56.2
Nickel	0.37	Neodymium	40
Neodymium	0.20	Magnesium	35
Magnesium	0.18	Lithium	21
Lithium	0.10	Titanium	16
Titanium	0.087	Aluminum	9.4
Cobalt	0.079	Nickel	9.1
Copper	0.069	Cobalt	8.3
Molybdenum	0.061	Tin	6
Aluminum	0.051	Copper	4.1
Lead	0.039	Zinc	2.8
Tin	0.021	Lead	2.5
Zinc	0.010	Molybdenum	2.5
Iron	0.005	Iron	2.4

Based on data by PE International (2013)

The ecotoxicity potential differs significant when using different LCI data. In Table A.9 an exemplary overview of characterization results based on different LCI data sets are presented (supplementing Chapter 5.3). In the brackets the processes used as a basis for the comparison are indicated.

Table A.9: Ecotoxicity potential [CTUe], based on LCI data by PE International and ecoinvent

	Ecotoxicity [CTUe] based on PE International	Ecotoxicity [CTUe] based on ecoinvent
Cadmium	2.6 [GLO: Cadmium]	9.1 [GLO: cadmium, primary, at plant]
Gold	1254 [GLO: Gold mix]	13425380 [GLO: gold, primary, at refinery]
Nickel	6.4 [GLO: Nickel mix]	1542 [GLO: nickel, 99,5%, at plant]
Silver	221 [GLO: Silver mix]	163817 [GLO: silver, at refinery]

Based on data by PE International (2013), ecoinvent centre (2010), and USEtox (2013)

Sensitivity analysis: CML vs. ReCiPe (see Chapter 5.3)

Regarding potential impacts of GHG emissions, CML categorizes impacts as “Global Warming Potential” and ReCiPe as “Climate Change”. Both methods provide similar results, due to the similarity of evaluation methods used (Figure A.4). The minor differences in results obtained are caused by ReCiPe not accounting for biogenic sequestration of CO_2-emissions by renewable resources (CML 2013; Goedkoop et al. 2008).

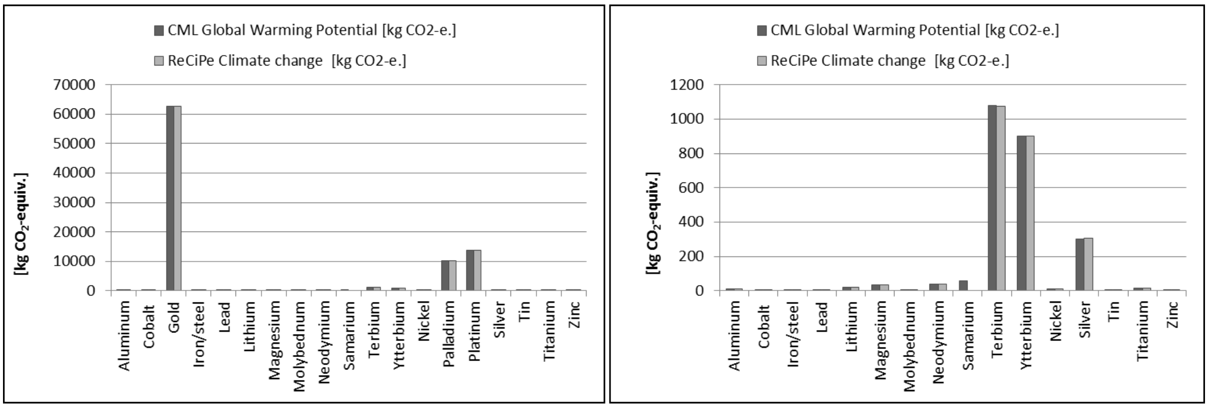

Figure A.4: CML vs. ReCiPe – Potential impacts of GHG emissions (left)**, and excluding *gold*, *palladium, and platinum*** (right)

In Figure A.5 the results of the AP are shown. Regarding acidification, both methods use the same reference unit (kg SO_2-e.). However, in the CML method results are calculated based on 141 different flows, while results according to ReCiPe are based only on four different flows. Regarding *ytterbium* significant differences occur as not all emissions assessed within the CML evaluation are covered by the ReCiPe-method. Within the CML-method, most relevant emissions for acidification are hydrogen chloride, nitrogen oxides and sulfur dioxide. The ReCiPe-method does not consider emissions of hydrogen chloride. As the amount of hydrochloric acids used for the production of *ytterbium* is higher than compared to the other rare earths (see Chapter 5.3.), the difference in results is more significant here. Nevertheless, both methods provide similar results for the different materials.

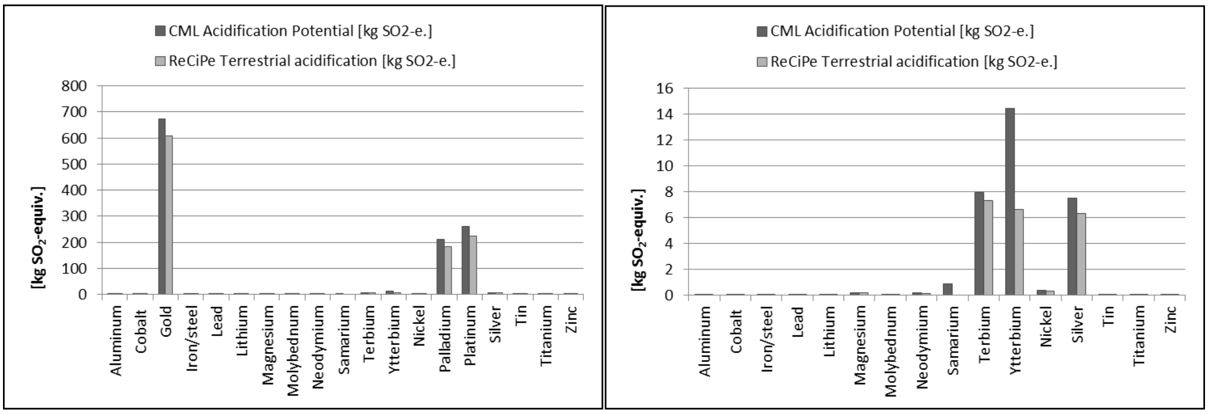

Figure A.5: CML vs. ReCiPe – Potential impacts of acidifying substances (left)**, and excluding *gold*, *palladium, and platinum*** (right)

APPENDIX V

Chapter 3 and 4 of this dissertation are based on publications in the International Journal of Life Cycle Assessment. These publications are enclosed in the following.

Paper I: Schneider L, Berger M, Finkbeiner M (2011) The anthropogenic stock extended abiotic depletion potential (AADP) as a new parameterization to model the depletion of abiotic resources. International Journal of Life Cycle Assessment 16 (9):929-936

Paper II: Schneider L, Berger M, Schüler-Hainsch E, Knöfel S, Ruhland K, Mosig J, Bach V, Finkbeiner M (2013) The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment. International Journal of Life Cycle Assessment 19 (3): 601-610

Int J Life Cycle Assess (2011) 16:929–936
DOI 10.1007/s11367-011-0313-7

LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The anthropogenic stock extended abiotic depletion potential (AADP) as a new parameterisation to model the depletion of abiotic resources

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Abstract
Purpose Raw material availability is a cause of concern for many industrial sectors. When addressing resource consumption in life cycle assessment (LCA), current characterisation models for depletion of abiotic resources provide characterisation factors based on (surplus) energy, exergy, or extraction–reserve ratios. However, all indicators presently available share a shortcoming as they neglect the fact that large amounts of raw materials can be stored in material cycles within the technosphere. These "anthropogenic stocks" represent a significant source and can change the material availability significantly. With new characterisation factors, resource consumption in LCA will be assessed by taking into account anthropogenic material stocks in addition to the lithospheric stocks. With these characterisation factors, the scarcity of resources should be reflected more realistically.
Materials and methods This study introduces new characterisation factors—the anthropogenic stock extended abiotic depletion potentials—for the impact category depletion of abiotic resources. The underlying characterisation model is based on the conventional model but substitutes *ultimate reserves* by *resources* and adds anthropogenic material stocks to the lithospheric stocks.
Results and discussion A fictional life cycle inventory, consisting of 1 kg of several metals, was evaluated using different characterisation factors for depletion of abiotic resources. Within this analysis it is revealed that materials with relatively large anthropogenic stocks, e.g. *antimony* and *mercury*, contribute comparatively less to abiotic depletion when using the new characterisation factors. Within a normalized comparison of characterisation factors, the impact of anthropogenic stock results in relative differences between −45% and +65%, indicating that anthropogenic stocks are significant.
Conclusions With the new parameterisation of the model, depletion of abiotic resources can be assessed in a meaningful way, enabling a more realistic material availability analysis within life cycle impact assessment. However, a larger set of characterisation factors and further research are needed to verify the applicability of the concept within LCA practice.

Keywords Abiotic depletion potential · Anthropogenic stock · LCA · Material availability · MFA

1 Introduction

1.1 Background and objective

Humankind has consumed more minerals during the past century than in all earlier centuries together (Tilton 2003). The problem with the consumption of those resources is their decreasing availability for future generations (Brentrup et al. 2002). As raw materials are important for most industrial sectors, potential scarcity is a matter of concern for many stakeholders. In current life cycle impact assessment (LCIA) practice (ISO 14040 2006), resource use is evaluated by means of indicators based on (surplus) energy to mine this resource (Goedkoop and Spriensma 2001; PE International 2010), exergy of all resources required to provide a product (Bösch et al. 2007), or by means of the ratio of raw material extraction to lithospheric stock of this material, the abiotic depletion potential (ADP,

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Guinée et al. 2001). In a previous study (Berger and Finkbeiner 2011), significant correlations (R^2 up to 0.96) between those indicators have been revealed demonstrating that the results obtained in LCIA are rather independent from the impact category chosen. Thus, a closer assessment of one indicator appears to be sufficient for the consideration of resource use.

Gerst and Graedel (2008) pointed out that the continued increase in the use of metals over the twentieth century has led to the phenomenon of a substantial shift in metal stocks from the lithosphere to the anthroposphere. As this stock will become available in the future for recycling and reuse, the accumulated stocks in society have to be acknowledged when assessing the future resource availability or the depletion potential of a material. As resources are depleted only when they leave the economy in a form that functionality can no longer be restored (Stewart and Weidema 2005), these "anthropogenic stocks" represent a significant source and can change raw material availability significantly (Kapur and Graedel 2006; Brunner and Rechberger 2004). Yet, so far, all indicators neglect the fact that large amounts of raw materials are stored in material cycles within the technosphere. Thus the aim of the study is to introduce new characterisation factors, the anthropogenic stock extended abiotic depletion potentials (AADP), for the impact category depletion of abiotic resources. With the new characterisation factors, resource consumption in LCA is assessed by taking into account anthropogenic material stocks in addition to the lithospheric stocks. With this characterisation factor, the scarcity of resources should be reflected more realistically. To include the anthropogenic stock into the assessment of resource depletion, data from material flow analyses (MFA) can be used (Brunner and Rechberger 2004). The analysis of material flows is already an important part of every LCA. But here flows are always associated to one product and not related to the whole material cycle. As MFA provides important insights, an inclusion of aspects into the environmental assessment of products seems meaningful.

After determining a set of characterisation factors for relevant metals, the new method is applied and tested in a theoretical case study. The results are evaluated and compared to results obtained by means of the conventional ADP (Guinée 1995; Guinée et al. 2001; van Oers et al. 2002) underlining the relevance of this enhancement.

1.2 Definitions and data

In the following sections, relevant terms related to the calculation of the abiotic depletion potential are defined according to existing definitions (see also Fig. 1). The *ultimate reserves*, so far used to assess ADP in the default characterisation model, are defined as the amount of a

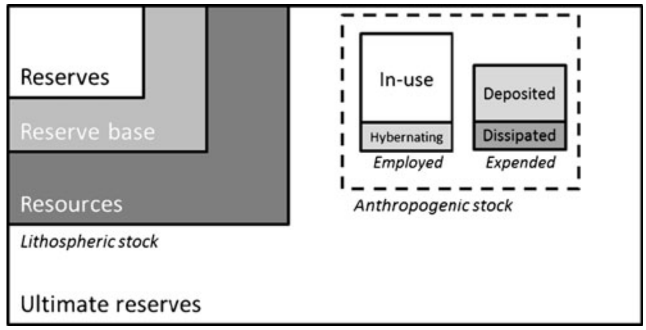

Fig. 1 Types of lithospheric and anthropogenic material stocks (based on Kapur and Graedel (2006)

resources that is ultimately available in the earth's crust (natural concentration of the resource multiplied by the mass of the crust) (van Oers et al. 2002; Guinée 1995). The definition of *ultimate reserves* comprises the total deposits of an element in the earth's crust without considering its actual concentration (Brentrup et al. 2002). *Reserves*, *reserve base*, and *resources* describe amounts of material with different anticipated time horizons concerning availability. Is the deposit rich enough to be mined at a profit today, it is termed (economic) *reserve*. Deposits that fulfil minimum physical and chemical criteria but are not economically extractable at the moment plus the *reserve* are termed *reserve base*. A *resource* describes the amount of mineral in such concentrated form that economic extraction is currently or potentially feasible (USGS 2010b; Kapur and Graedel 2006).

When referring to the anthropogenic stock, metals can also exist in different conditions which give an indication about the actual availability of the material. *Employed stock* is the amount represented in the anthroposphere that is still in use and not yet discarded while *hibernating stock* represent the amount of resource that is not used anymore, but which has not been discarded yet, either. *Expended stock* is the total amount of resource that has been discarded. Thereby, the *deposited stock* is the amount of the resource that has been deposited, in, e.g. landfills, and the *dissipated stock* is the amount of a resource that has been returned to nature in a form that makes recovery almost impossible (Kapur and Graedel 2006). In Fig. 1 the interrelation between the different kinds of material stocks are displayed (not drawn to scale).

Until recently, the main focus of MFA was on flows. During past years however, it was realized that material stocks may be equally or sometimes even more important (e.g. Kleijn et al. 2000; Müller et al. 2006; Rauch 2009). By dynamically analysing the flow of materials, information about the stock in society can be obtained (see, i.a. Daigo et al. 2007; Hatayama et al. 2010, 2007). Yet, as MFA is time consuming and complicated to conduct, especially with a global focus, existing data are limited and uncertainties are not quantified.

Currently, data for anthropogenic stocks generated through MFA are available for a limited number of materials only (UNEP 2010). For this reason, anthropogenic stocks in this study were determined as the accumulated extraction rate since the beginning of records, in approximately 1900, until 2008 based on data from the U.S. Geological Survey (USGS 2010a). It is assumed that the amount of materials mined before is negligibly low in comparison to the large volumes and rates extracted since 1900. The material is present in the technosphere as either *in-use*, *hibernating*, *deposited*, or *dissipated anthropogenic stock*. Hence, the total mass of one metal in society, regardless of its chemical form, is included in the assessment of the anthropogenic stock (UNEP 2010). It should however be noted that the *dissipated stock*, which comprises the fraction of anthropogenic stocks that is lost due to, e.g. leaching or chemical reactions (Kapur and Graedel 2006), should actually be subtracted from the total anthropogenic stock in the calculation. As detailed material flow analysis of *copper* has shown that the *dissipated stock* accounts for less than 1% (Kapur and Graedel 2006), this is neglected in this study for the time being. However, it has to be acknowledged that materials have different characteristics that influence the amount of dissipation. For a more accurate analysis, a close assessment of individual materials has to be conducted in future studies.

2 Methodology

2.1 System description

In this section the development of the new parameterisation of the characterisation model is described more closely. The adaptation of existing characterisation factors will be conducted in two steps: The first step refers to an adjustment of the lithospheric stock considered for the assessment of material depletion (discussed below), and the second step is the inclusion of the anthropogenic stock into the characterisation model.

Within the current ADP model (Guinée et al. 2001), the total amount of a material in the earth's crust is used. However, these *ultimate reserves* are not a good indicator to measure resource scarcity as they will never actually be used for mining (Müller-Wenk 1998) and cannot reflect shortages. Any material will eventually deplete, even if lower and lower grade ores are included in the extraction, as costs and impacts will become too high (Steen 2006). When providing the conventional ADP characterisation model, Guinée (1995) already pointed out that rather the consideration of the *ultimately extractable reserve* would be the relevant parameter with regard to depletion.

Adjustments of the conventional model have been proposed before. Following the assumption of Brentrup et al. (2002), only *reserves* should be applied as *reserve base* or *resources* are dependent on further technical developments which are not considered within LCA. Guinée et al. (2001) and van Oers et al. (2002) already proposed to use the *economic reserves* instead of the *ultimate reserves* in an alternative characterisation model. Yet, these economic *reserves* and also the *reserve base* are actually not directly related to the depletion problem, as noted by Guinée (1995), but more an economic parameter, subject to constant change as directly dependent on the price of a material.

A valid, long-term assessment has to acknowledge the relevance of technical improvements as these are actually a main incentive to conduct LCAs and are important with regard to resource use. Moreover, for the inclusion of anthropogenic stocks into the assessment, consistency with lithospheric stocks regarding the availability time frame has to be considered. In this paper determination of the anthropogenic stock, as described in the introduction, is based on the theoretical extractable amount in society (disregarding the *dissipated stock*).

For the combination of lithospheric and anthropogenic stocks, it is important to merge consistent stocks which provide similar availability characteristics with regard to occurrence and concentration. Thus, and also as discussed by Guinée (1995) and van Oers et al. (2002), the determination of geological availability within this work should also be oriented on the extractable amount of a resource. However, these geological reserves are hard to detect, and hence an approximation has to be used. As the consistency of anthropogenic stocks and reserve figure used is of importance, geological reserves for this study are best described with *resources* (according to the U.S. Geological Survey (2010c)). *Resources* are by definition located between *reserve base* and *ultimate reserves*, and thus closest to the definition of *ultimately extractable reserves* (Guinée 1995; van Oers et al. 2002). Therefore it seems consistent to combine *resources* and the total anthropogenic stock as both describe deposits for which extraction is currently or potentially feasible and both depend on the technological and economic development in the future.

2.2 Characterisation model

In their default characterisation model, Guinée et al. (2001) determined the characterisation factors for depletion of abiotic resources.

$$\mathrm{ADP}_{i,\ \text{ultimate reserves}} = \frac{\text{extraction rate } i}{(\text{ultimate reserves } i)^2} \times \frac{(\text{ultimate reserves antimony})^2}{\text{extraction rate antimony}} \tag{1}$$

As shown in Eq. 1, $\mathrm{ADP}_{i,\ \text{ultimate reserves}}$ is calculated by first dividing the extraction rate of raw material *i* by the square of the ultimate reserves of raw material i in total available on earth. Second, this ratio is put in relation to the extraction–ultimate reserve ratio of the reference resource *antimony*. The contribution to the depletion of abiotic resources of a product is calculated by multiplying each raw material input (m_i) into the product system under study by its corresponding characterisation factor, the abiotic depletion potential (ADP_i, see Eq. 2) (Guinée et al. 2001).

$$ADP = \Sigma ADP_i \times m_i \tag{2}$$

In order to determine the new characterisation factors AADP, the characterisation models proposed by Guinée et al. (2001) are modified in two steps. First, resources are used instead of ultimate or economic reserves (see Eq. 3).

$$ADP_{i,\ \text{resources}} = \frac{\text{extraction rate } i}{(\text{resources } i)^2} \times \frac{(\text{resources antimony})^2}{\text{extraction rate antimony}} \tag{3}$$

Second, the anthropogenic stock of a raw material (as defined in previous sections) is added to the resource (see Eq. 4).

$$AADP_{i,\ \text{resources}} = \frac{\text{extraction rate } i}{(\text{resources } i + \text{anthropogenic stock } i)^2} \times \frac{(\text{resources antimony} + \text{anthropogenic stock antimony})^2}{\text{extraction rate antimony}} \tag{4}$$

In this study all data for extraction rates, resources, and stocks were derived from the USGS (e.g. 2010b). For conventional ADP values according to the CML guideline (Guinée et al. 2001) are applied.

The impact assessment for the category depletion of abiotic resources was accomplished by applying the conventional ADP (Guinée et al. 2001), the same model, but replacing ultimate reserves with resources ($ADP_{resources}$) and the AADP. The characterisation factor $ADP_{resources}$ was added for identifying the actual influence anthropogenic stocks have on the results. Based on the characterisation models shown in Eqs. 3 and 4, characterisation factors for a range of relevant metals are calculated and the newly parameterised model is tested by evaluating a fictional life cycle inventory. For simplicity the fictional inventory contains the elementary input flows of 1 kg of each material.

3 Results and discussion

On the basis of the characterisation model described in the previous section, abiotic depletion potentials were calculated. For now, due to limited data access, the focus of this study is on ten materials only. Future work will encompass a larger set of materials focusing especially on scarce metals and potential relief through the inclusion of anthropogenic stocks into the assessment. Table 1 shows $ADP_{resources}$ and AADP characterisation factors derived from the conventional ADP characterisation model (Guinée et al. 2001).

The assumption that $ADP_{resources}$ and AADP factors should be larger than ADP factors because material availability decreases when *resources* and anthropogenic stocks are used instead of *ultimate reserves*, however, is not necessarily the case. As all factors express the result in relation to the reference resource *antimony*, the characterisation factors can hardly be compared directly. Only the ratio of, e.g. $ADP_{resources,\ Cu}$ to $ADP_{resource,\ Ni}$ can be compared to the ratio of $AADP_{Cu}$ and $AADP_{Ni}$. For the AADP, the difference between the ratios is dependent on the anthropogenic stock-

Table 1 Characterisation factors for material portfolio

Raw material	Extraction rate [t/a][a]	Resource [t][b]	Anthropogenic stock [t][c]	ADP [t Sb-e./kg][d]	$ADP_{resources}$ [t Sb-e./t]	AADP [t Sb-e./t]
Al	3.90E+07	7.50E+10	8.73E+08	1.00E-08	1.27E-06	5.34E-06
Cd	2.01E+04	6.00E+06	1.04E+06	3.30E-01	1.02E-01	3.19E-01
Co	7.59E+04	1.50E+07	1.94E+06	2.62E-05	6.18E-02	2.08E-01
Cu	1.57E+07	2.30E+09	5.11E+08	1.94E-03	5.44E-04	1.57E-03
Fe	2.22E+09	8.00E+11	5.71E+10	8.43E-08	6.36E-07	2.38E-06
Hg	1.32E+03	6.00E+05	5.46E+05	4.95E-01	6.72E-01	7.92E-01
Ni	1.57E+06	1.30E+08	4.78E+07	1.08E-04	1.70E-02	3.91E-02
Pb	3.80E+06	1.50E+09	2.17E+08	1.35E-02	3.10E-04	1.02E-03
Sb	1.65E+05	5.50E+06	5.90E+06	1.00E+00	1.00E+00	1.00E+00
Zn	1.16E+07	1.90E+09	4.18E+08	9.92E-04	5.89E-04	1.70E-03

[a] USGS (2010b)

[b] Butterman and Carlin (2004), Deutsches Kupferinstitut (2011), Frondel et al. (2006), Hill and Sehnke (2006), and USGS (2007, 2010b)

[c] USGS (2010a)

[d] According to Guinée (1995) and Guinée et al. (2001)

resource relation of the materials. Hence, materials with relatively large anthropogenic stocks will contribute comparatively less to abiotic depletion than materials with relatively low anthropogenic stocks (Berger et al. 2010).

This rather theoretical discussion is illustrated by means of the case study in which a fictional life cycle inventory, consisting of 1 kg of each metal, was evaluated using ADP, $ADP_{resources}$, and AADP. The results on the inventory level and for the impact category depletion of abiotic resources when using ADP, $ADP_{resources}$, or AADP characterisation factors are shown in Fig. 2.

In Fig. 2 only cadmium (Cd), mercury (Hg), and antimony (Sb) contribute to the impact assessment results in a noticeable manner while the remaining metals cause minor impacts only. Overall comparing the results of ADP, $ADP_{resources}$, and AADP, it appears that no big differences are obtained by means of the new parameterisation of the characterisation model. Even though, e.g. cobalt (Co), which is not significant for ADP, has a contribution to $ADP_{resources}$ and AADP, the result is also dominated by the impacts resulting from the abiotic depletion of antimony, mercury, and cadmium—with a similar percentage contribution. Considering the equally distributed inventory containing 1 kg of each metal, the relative values in Fig. 2 also reflect a direct comparison of the characterisation factors shown in Table 1. As characterisation factors for cadmium, mercury, and antimony are largest and similarly distributed in ADP and AADP, it is logical that they dominate the results and lead to similar findings. Hence, one should not generalize that no differences are obtained by means of the new characterisation factors. In a second analysis shown in Fig. 3, the dominating metals were excluded from the analysis and the results are again displayed using ADP, $ADP_{resources}$, and AADP characterisation models.

While ADP results in Fig. 3 are dominated by the abiotic depletion of lead (Pb), cobalt and nickel (Ni) contribute most to the $ADP_{resources}$ and AADP category indicator result, with slight differences. Hence, lead is regarded as the scarcest metal in the inventory when computing characterisation factors based on the ratio of extraction rate to ultimate reserves. In contrast, when calculating extraction–reserve ratios by means of the sum of *resources* or *resources* and anthropogenic stocks, lead is of less importance and cobalt is regarded as the most critical metal, followed by nickel. Obviously, criticality of certain materials is different with regard to the new characterisation factors, providing different implications for decisions. In Fig. 2 a visible difference between $ADP_{resources}$ and AADP can be found. For example antimony and mercury stocks are larger or almost as large as the *resources*. Thus the pressure displayed by the $ADP_{resources}$ should be higher than compared to the pressure displayed by AADP. By means of Fig. 2 this can be verified. Large stocks are thus reducing the pressure on a resource and have a comparably lower impact on the depletion of abiotic resources. The difference between $ADP_{resources}$ and AADP characterisation factors displayed in Fig. 3 seems to be small. Therefore, in Fig. 4, the difference of the characterisation models is displayed more closely to emphasize the significance of the new approach. Hereby all factors are normalized to copper (Cu) for an easier interpretation of results.

For materials with large anthropogenic stocks, the characterisation factor is decreasing because the denominator is increasing. By assessing the relative change compared to copper, e.g. $AADP_{Ni}$ to $AADP_{Cu}$, the large nickel stock will lead to a smaller ratio than the same comparison for $ADP_{resources}$. This confirms that the consideration of anthropogenic stocks leads to different impacts for materials within the characterisation models (here, materials with larger anthropogenic stocks than copper (mercury, antimony, and nickel) contribute comparably less to abiotic depletion). Positive bars in Fig. 4 represent values beneath 100% for AADP/ADPresources, standing for a

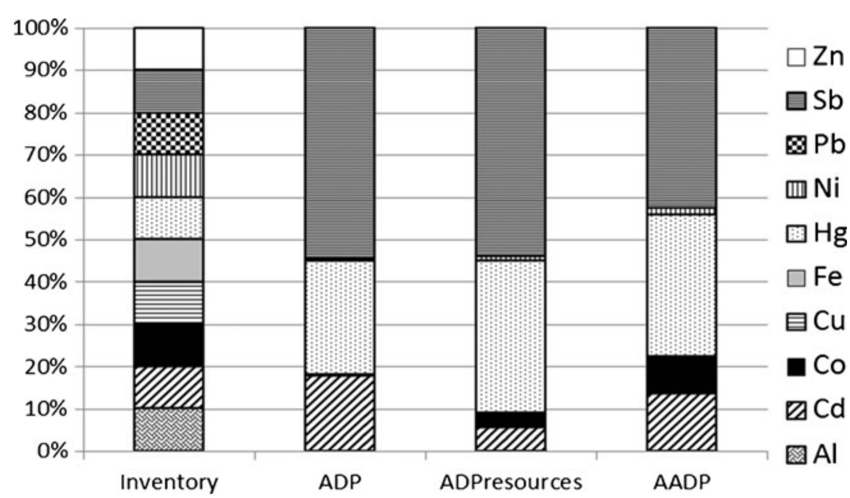

Fig. 2 Contribution of metals to the impact category depletion of abiotic resources

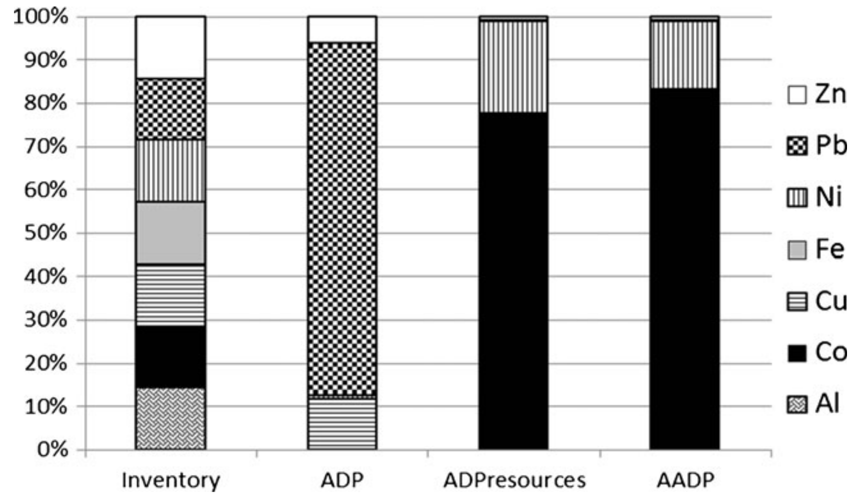

Fig. 3 Contribution of selected metals to the impact category depletion of abiotic resources

comparably lower depletion potential compared to copper when applying AADP, and vice versa. Given that in Fig. 3 the contribution is displayed as a function of the sum of all characterisation factors, these differences are not as obvious. With growing anthropogenic stocks and increasing data availability, the AADP characterisation factors will become more important for a realistic assessment of resource depletion. It is revealed that the impact of anthropogenic stock results in relative differences between −45% and +65%, indicating that anthropogenic stocks are significant.

As stated within the definition of the conventional ADP characterisation factor (Guinée 1995), reserves of a material are taken into account more than once (by putting a square to the denominator (see Eq. 1)) to provide a realistic depiction of resource criticality (when assessing the effect of 1 kg of extraction). Underlying is the fact that small stocks are a more important indicator for resources depletion than large extraction rates. Simply comparing extraction rates and stocks would lead to different results. This implies that the stocks of materials have a comparably higher importance than extraction rates within the calculation of characterisation factors (Guinée 1995). Thus, the difference between the extraction rates used for conventional ADP and for $ADP_{resources}$/AADP (USGS 2010b) should not be a determining factor. It seems that the AADP characterisation model can enable a more realistic assessment of depletion of abiotic resources with regard to, e.g. the implementation of new technologies.

However, there are still challenges which currently remain unsolved. The lack of data concerning *resources* and anthropogenic stocks inhibits the calculation of a larger set of characterisation factors. Furthermore, from a methodological point of view, it is still unclear how anthropogenic stocks can be calculated for, e.g. fossil fuels, for which plastics available in the technosphere might serve as anthropogenic deposit to a certain degree.

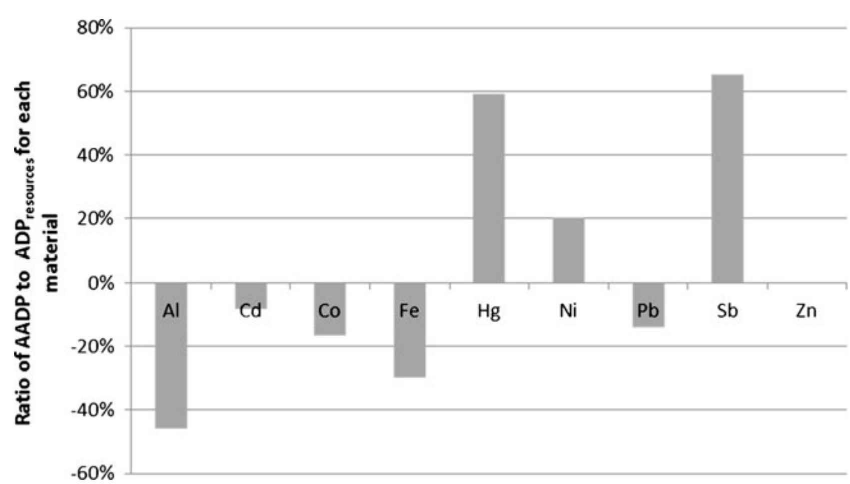

Fig. 4 Characterisation factors $ADP_{resources}$ compared to AADP (normalized to copper)

4 Conclusions and outlook

In order to allow for a more realistic material availability assessment, a new parameterisation of the characterisation model for depletion of abiotic resources was introduced. A case study in which a fictional life cycle inventory was assessed using ADP, $ADP_{resources}$, and AADP characterization models revealed different results. Metals like cobalt and nickel, which are perceived as critical for future technologies (e.g. Angerer et al. 2009), do not influence the ADP result at all. As these metals contribute more to the AADP category indicator result, the new parameterisation seems to enable a more realistic assessment of resource use in LCA. The differences assessed between $ADP_{resources}$ and AADP underline the relevance of anthropogenic stocks for the assessment of abiotic depletion. However, a larger set of characterisation factors and further research are needed to verify the applicability of the concept within LCA practice.

There are some challenges associated with this new parameterisation and the inclusion of the anthropogenic stock into the calculation of abiotic depletion potentials. The classification of the anthropogenic stock is complicated and requires thorough analysis as it occurs in many different states within the anthroposphere. This makes an exact quantification difficult as measurement of the recoverable part of anthropogenic stocks is complicated. Besides, the quality of recovered materials might not be sufficient for certain applications, or large amounts of the material are subject to degradation in the atmosphere (Graedel and McGill 1986). Such restrictions need to be addressed in future studies and have to be determined for every material individually (Stewart and Weidema 2005). Furthermore, each material is unique and the depletion of natural minerals represents different environmental problems (van Oers et al. 2002; Brentrup et al. 2002). The inclusion of anthropogenic stock is considered to have a positive effect within this study. However, in reality, anthropogenic stocks can also induce environmental pressure, e.g. due to material dissipation from *in-use stocks*. Thus, larger stocks could also have negative effects on the environment. For future advancements anthropogenic stocks should be considered extensively within life cycle assessment. In addition to the "geological assessment" of resource availability, ongoing work also encompasses the evaluation of economic material availability within life cycle sustainability assessment (Schneider et al. 2011).

The future resource assessment has to be advanced to meaningfully consider more aspects associated with the extraction and use of resource. The developed characterisation factors still lack significance due to data uncertainties, especially on the global level. However, with improving inputs by means of MFA, the characterisation factors will gain increasing importance for the assessment of depletion of abiotic resources within LCA. A comprehensive approach by enhancing LCA with MFA data is important for future decision making.

References

Angerer G, Erdmann L, Marscheider-Weidemann F, Scharp M, Lüllmann A, Handke V, Marwede M (2009) Rohstoffe für Zukunftstechnologien. Fraunhofer IRB Verlag, Stuttgart

Berger M, Finkbeiner M (2011) Correlation analysis of life cycle impact assessment indicators measuring resource use. Int J Life Cycle Assess 16:75–81

Berger M, Schneider L, Finkbeiner M (2010) A new characterization model for depletion of abiotic resources—the antrhopogenic stock extended abiotic depletion potential. In: The 9th International Conference on EcoBalance, Tokyo, 9–12 November 2010

Bösch ME, Hellweg S, Huijbregts MAJ, Frischknecht R (2007) Applying cumulative exergy demand (CExD) indicators to the ecoinvent database. Int J Life Cycle Assess 12:181–190

Brentrup F, Küsters J, Lammel J, Kuhlmann H (2002) Impact assessment of abiotic resource consumption. Int J Life Cycle Asses 7(5):301–307

Brunner PH, Rechberger H (2004) Practical handbook of material flow analysis. Lewis Publishers, Boca Raton

Butterman WC, Carlin JF (2004) Antimony. Mineral commodity profiles. U.S. Geological Survey

Daigo I, Igarashi Y, Matsuno Y, Adachi Y (2007) Accounting for steel stock in Japan. ISIJ Int 47(7):1065–1069

Deutsches Kupferinstitut (2011) Vorkommen und Gewinnung. http://www.kupfer-institut.de/front_frame/frameset.php3?client=1&lang=1&idcat=34&parent=14. Accessed 22 Feb 2011

Frondel M, Angerer G, Buchholz P, Grösche P, Huchtemann D, Oberheitman A, Peters J, Vance C, Sartorius C, Röhling S, Wagner M (2006) Trends der Angebots- und Nachfragesituation bei mineralischen Rohstoffen. Rheinisch-Westfälisches Institut für Wirtschaftsforschung, Fraunhofer-Institut für System- und Innovationsforschung, Bundesanstalt für Geowissenschaften und Rohstoffe

Gerst MD, Graedel TE (2008) In-use stocks of metals: status and implications. Environ Sci Technol 42(19):7038–7045

Goedkoop M, Spriensma R (2001) The Eco-indicator 99—a damage oriented method for life cycle impact assessment. Product Ecology Consultants (PRe), Amersfoort

Graedel TE, McGill R (1986) Degradation of materials in the atmosphere. Environ Sci Technol 20(11):1093–1100

Guinée JB (1995) Development of a methodology for the environmental life-cycle assessment of products; with a case study on margarines. Leiden University

Guinée JB, de Bruijn H, van Duin R, Gorree M, Heijungs R, Huijbregts MAJ, Huppes G, Kleijn R, de Koning A, van Oers L, Sleeswijk AW, Suh S, de Haes HA Udo (2001) Life cycle assessment—an operational guide to the ISO standards, part 2b. Centre of Environmental Science—Leiden University (CML), Leiden

Hatayama H, Yamada H, Daigo I, Matsuno Y, Adachi Y (2007) Dynamic substance flow analysis of aluminium and its alloying elements. Mater Trans 48(9):2518–2524

Hatayama H, Daigo I, Matsuno Y, Adachi Y (2010) Outlook of the world steel cycle based on the stock and flow dynamics. Environ Sci Technol 44(16):6457–6463

Hill VG, Sehnke ED (2006) Bauxite. In: Kogel JE, Trivedi NC, Barker JM, Krukowski ST (eds) Industrial minerals and rocks. SME, Littleton

ISO 14040 (2006) Environmental management—life cycle assessment—principles and framework (ISO 14040:2006). European Committee for Standardisation, Brussels

Kapur A, Graedel TE (2006) Copper mines above and below the ground. Environ Sci Technol 40(10):3135–3141

Kleijn R, Huele R, Evd V (2000) Dynamic substance flow analysis: the delaying mechanism of stocks, with the case of PVC in Sweden. Ecol Econ 32:241–254

Müller DB, Wang T, Duval B, Graedel TE (2006) Exploring the engine of anthropogenic iron cycles. PNAS 103(44):16111–16116

Müller-Wenk R (1998) Depletion of abiotic resources weighted on base of "virtual" impacts of lower grade deposits used in future. Institut für Wirtschaft und Ökologie, St. Gallen

PE International (2010) http://www.gabi-software.com. Accessed 20 Dec 2010

Rauch JN (2009) Global mapping of Al, Cu, Fe, and Zn in-use stocks and in-ground resources. PNAS 106(45):18920–18925

Schneider L, Berger M, Finkbeiner M (2011) Economic material availability as a new area of protection for life cycle sustainability assessment. In: SETAC Europe 2011, Milano

Steen BA (2006) Abiotic resource depletion. Int J Life Cycle Assess 11(Special Issue 1):49–54

Stewart M, Weidema B (2005) A consistent framework for assessing the impacts from resource use. Int J Life Cycle Assess 10 (4):240–247

Tilton JE (2003) On borrowed time? Assessing the threat of mineral depletion. Resources for the Future, Washington

UNEP (2010) Metal stocks in society—scientific synthesis. International Panel for Sustainable Resource Management

USGS (2007) Cadmium. Mineral commodity summaries. U.S. Geological Survey

USGS (2010a) Historical statistics for mineral and material commodities in the United States. U.S. Geological Survey, Washington

USGS (2010b) Mineral commodity summaries. U.S. Geological Survey, Washington

USGS (2010c) Mineral commodity summaries. Appendix C. U.S. Geological Survey, Washington

van Oers L, deKoning A, Guniée JB, Huppes G (2002) Abiotic resource depletion in LCA. Road and Hydraulic Engineering Institute

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LIFE CYCLE SUSTAINABILITY ASSESSMENT

The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment

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Abstract
Purpose In life cycle assessment (LCA), resource availability is currently evaluated by means of models based on depletion time, surplus energy, etc. Economic aspects influencing the security of supply and affecting availability of resources for human use are neglected. The aim of this work is the development of a new model for the assessment of resource provision capability from an economic angle, complementing existing LCA models. The inclusion of criteria affecting the economic system enables an identification of potential supply risks associated with resource use. In step with actual practice, such an assessment provides added value compared to conventional (environmental) resource assessment within LCA. Analysis of resource availability including economic information is of major importance to sustain industrial production.
Methods New impact categories and characterization models are developed for the assessment of economic resource availability based on existing LCA methodology and terminology. A single score result can be calculated providing information about the economic resource scarcity potential (ESP) of different resources. Based on a life cycle perspective, the supply risk associated with resource use can be assessed, and bottlenecks within the supply chain can be identified. The analysis can be conducted in connection with existing LCA procedures and in line with current resource assessment practice and facilitates easy implementation on an organizational level.
Results and discussion A portfolio of 17 metals is assessed based on different impact categories. Different impact factors are calculated, enabling identification of high-risk metals. Furthermore, a comparison of ESP and abiotic depletion potential (ADP) is conducted. Availability of resources differs significantly when economic aspects are taken into account in addition to geologic availability. Resources assumed uncritical based on ADP results, such as rare earths, turn out to be associated with high supply risks.
Conclusions The model developed in this work allows for a more realistic assessment of resource availability beyond geologic finiteness. The new impact categories provide organizations with a practical measure to identify supply risks associated with resources. The assessment delivers a basis for developing appropriate mitigation measures and for increasing resilience towards supply disruptions. By including an economic dimension into resource availability assessment, a contribution towards life cycle sustainability assessment (LCSA) is achieved.

Keywords Economic criteria · LCA · LCSA · Resource availability · Scarcity · Supply risk

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1 Introduction

Access to resources "is often seen as a precondition for economic development" (UNEP 2010), and analysis of resource availability is of major importance to secure future supply (the term resources as used in this paper refers to geologic resources, raw materials, materials and energy carriers). A frequently applied method for the assessment of resource use of products and product systems is life cycle assessment (LCA). Within LCA, “resource provision capability for human welfare” (Udo de Haes et al. 2002; UNEP 2010) is defined as an area of protection (AoP), focusing on the removal of resources from the environment. By extracting resources, the concentration in the earth's crust is changed. However, if and to what extent biogeochemical cycles are affected and if potentially environmental changes occur due to resource depletion itself (and not the extraction) is not clear (Sala 2012). As resources have often rather an instrumental (availability for human use) than an environmental value, distinction between environmental and economic aspects of resource depletion is often not straightforward (Steen 2006; Udo de Haes et al. 2002; Weidema et al. 2005).

Even though resource depletion is not always seen as a true “environmental impact” and inclusion in environmental assessment is questioned (Finnveden 2005; UNEP 2010), evaluation of resource use and availability is common practice within LCA (European Commission 2010b; ISO 2006a, b). Existing models for the assessment of resource availability in LCA relate to energy and mass of a resource used, exergy or entropy impacts, future consequences of resource extraction (e.g., surplus energy, marginal cost), and diminishing geologic deposits, or assess environmental impacts of resource extraction (see i.a. BUWAL 1998; Finnveden et al. 2009; Goedkoop and Spriensma 2001; Guinée 2002; Hauschild and Wenzel 1998; Klinglmair et al. 2013; PE International 2012; Steen 2006; Stewart and Weidema 2005; van Oers et al. 2002).

However, these models focus on geologic finiteness and deliver no conclusion about actual resource availability at the site of production. Resources commonly perceived as scarce are not visible in the results (e.g., rare earth metals are up to this point of no relevance in the life cycle analysis of electric vehicles; Schneider et al. 2011b, 2013).

There are serious difficulties in defining the “problem” of resource depletion, and the lack of consensus leads to incongruent results. Especially in consideration of the fact that depletion or scarcity of resources can affect human productivity (Klinglmair et al. 2013; Weidema et al. 2005), a holistic and realistic assessment of resource use has to go beyond the analysis of mere (physical) availability of resources in the natural environment (Klinglmair et al. 2013) or the impacts of their extraction. A comprehensive analysis towards life cycle sustainability assessment (LCSA), including social and economic information, is needed to find more sustainable means of resource use.

The current AoP is used as a general category encompassing environmental considerations of resource depletion. However, a direct link to environmental consequences is missing. In fact, “resource provision capability for human welfare” is already aptly describing the general concern over the access to resources and the availability for human use, and implementation of the AoP needs to go beyond the current environmental focus and comprehensively address this issue. Supply risks concerning the continued resource provision capability ought to be assessed in addition to geologic availability. The focal point of the AoP needs to be extended to include limited supply (scarcity) of resources caused by economic (e.g., distributional or political) or social (e.g., human rights abuse) restraints or risks. The consideration of these additional dimensions complements existing models for the analysis of resources, as it goes beyond an environmental function towards the comprehensive assessment of resource availability in the context of LCSA.

In the present paper, criteria affecting economic systems (referred to as “economic criteria”) and ultimately resources availability are assessed complementary to existing environmental LCA models to sustain industrial production and to increase resilience towards supply disruptions (Graedel and Erdmann 2012; UNEP 2010). Within this study, new impact categories for the assessment of resource provision capability from an economic angle are developed and implemented. These impact categories cover a broad range of economic availability criteria and are applied for a portfolio of 17 metals.

Various papers and working groups are dealing with criticality of resource supply, but independently from a life cycle-based approach (i.a. Angerer et al. 2009a, b; defra 2012; Erdmann and Behrendt 2010; European Commission 2010a; Graedel et al. 2012a; Nassar et al. 2012; National Research Council 2008; Rosenau-Tornow et al. 2009; VDI 2013). Several of these studies aim at developing and applying a methodology to determine resource criticality with regard to certain systems, and quantitative scales are introduced to compare the supply risk of resources. For the availability assessment of resources consumed in a product system including a life cycle perspective, these scales are not meaningful due to the low margin of results. This means results would be mainly influenced by the quantity of the resource used but not by the respective supply risk.

2 Economic resource availability

In Table 1 an overview of several criteria potentially affecting resource availability and supply is provided. By analyzing such economic criteria, supply risks can be identified, and more informed decisions regarding choice and use of resources can be made.

In Section 2.1, criteria influencing supply risk and respective indicators for quantification of these criteria as used in this work are described in more detail. Section 2.2 describes the methodology of the proposed model for the assessment of resource availability from an economic angle in more detail.

Table 1 Exemplary overview of economic criteria potentially affecting resource supply

Availability of reserves	Coproduction/companion metal fraction
Economic stability	Potential for substitution
Concentration of reserves or production to certain countries	Competing technologies
Concentration of production activities to certain companies	Demand growth/change rate of demand
Trade barriers	Logistic constraints
Volatility	Availability of (exploitable) anthropogenic stocks
Price elasticity of demand and supply	Capacity utilization
Recycling/availability of secondary material	Availability of energy carriers
Societal acceptance of mining activities	Dissipative use of resources
Susceptibility to natural disasters	Investment in mining
Transportation costs	Production costs

2.1 Criteria and indicators

The criteria and indicator selection in this work takes up and complements existing works (see i.a. Erdmann and Behrendt 2010; Erdmann and Graedel 2011; European Commission 2010a; Graedel et al. 2012a; National Research Council 2008; Rosenau-Tornow et al. 2009; Yellishetty et al. 2011). All described criteria might affect the supply security of resources and consequently cause supply shortages. Regarding the selection of criteria and indicators for quantification, data availability proves to be the main limiting factor. Even though choice of criteria and indicators should be as broad as possible, several criteria have to be neglected at present as data availability and quality is poor (e.g., regarding the availability of anthropogenic stocks or potential for substitution). Chosen indicators are based on publicly available and accepted databases or publications. In the following paragraphs, indicators as used in this work are introduced in more detail.

Reserves have a physical as well as an economic dimension. Per definition of the USGS, reserves are "that part of a resource which could be economically extracted or produced at the time of determination" (USGS 2013) displaying current production technologies. Availability of resources can be assessed by means of the depletion time (reserve-to-production ratio). Even though the reserve-to-production ratio changes over time, it is a useful indicator to evaluate periodic availability of a resource (see, e.g., also Graedel et al. 2012b).

Recycling can be an efficient mechanism to secure supply (UNEP 2011). From a product perspective, primary metal consumption can be reduced by the use of secondary material, thus relieving pressure on virgin resource supplies (Graedel and Erdmann 2012). The recycled content is defined as the annual tonnage of material scrap consumed divided by the tonnage of material produced and depends on the amount of scrap available (European Commission 2010a; UNEP 2011). Thus, even with a high recycling rate, the recycled content can be low. The reverse of the recycled content, the new material content, indicates how much primary material is used in the production of a specific material on an average basis. As primary supply (as evaluated in this study) is subject to restrictions, the new material content provides a good reference for determination of supply risk.

A high *concentration* of one activity (e.g., mining) in few countries or a limited number of companies is always associated with a high risk regarding the accessibility of a resource. The assessment of country or company concentration is relevant at all stages of the supply chain. The Herfindahl-Hirschman Index (HHI) is a common measure of market concentration. The indicator is calculated by squaring the market share of each company or country with regard to the production/reserves and the summation of the results (von der Lippe 1993) (see also, e.g., Graedel et al. 2012b; Rosenau-Tornow et al. 2009).

Economic stability refers to risks related to policies, regulations, social progress, etc., that can have an effect on resource availability. Even though focus of this indicator is on overall investment and not on supply security of resources in specific (Rosenau-Tornow et al. 2009), the Worldwide Governance Indicators (WGI) are used as an approximation to model stability of governance processes of different countries (The World Bank Group 2012). As economic stability is dependent also on human development, in addition, the Human Development Index (HDI) is evaluated and included in the assessment for describing socioeconomic stability of different countries (Graedel et al. 2012a; UNDP 2011). The corresponding indicator represents a statistic for life expectancy, education, and income referring to social and economic development (UNDP 2011).

Demand growth can be assessed by means of past and future trends—based on future technologies, average annual growth rates, etc. Demand growth can be used to indicate potential pressure on timely supply. In this study, annual growth rates for the resources are considered. If available, future demand scenarios are included in the calculation of the indicator (Angerer et al. 2009a; USGS 2005, 2013).

Trade barriers are government-induced restrictions on international trade by means of, e.g., export quotas, taxes, tariffs, etc., leading to increasing prices or physical shortages of resources. The respective indicator represents the percentage of production of a certain resource underlying barriers. Any potential barrier to trade is considered (including tariff and nontariff measures) (BDI 2010).

Companion metal fraction describes the supply risk associated with resources that depend on the magnitude of mining of carrier or "host" metals (Graedel et al. 2012a; Graedel and Erdmann 2012). Availability of companion metals is strongly dependent on the demand for the carrier metal as companion metals cannot be mined economically by themselves. The interconnectivity of resources plays an important role in the determination of supply risk associated with individual resources due to complex pricing and technical limits to adapt production (Hagelüken and Meskers 2010; Reuter et al. 2005). Carrier metals are in general considered to be less vulnerable to supply risk than companion metals. Thus, as an indicator the percentage of a metal mined as companion metal is used to assess potential supply risk. As limited data is available, default values were also used based on data published by Erdmann and Behrendt (2010).

To what extent these criteria affect availability of individual resources and pose a threat to continued supply is assessed within this work. An analysis of interrelations of individual criteria is out of the scope of this work but will be included in future studies.

Many of the assessed indicators should be considered at several stages of the supply chain. Economic constraints can occur at any production stage (e.g., mining, refining, or distribution). In the present paper, for simplification and due to limited data availability, only the mine production (raw material stage) is assessed. In further works, an assessment of these other supply chain stages needs to be included to cover all potential restrictions and risks associated with the supply of materials like copper or steel (e.g., over 70 % of the seaborne trade of iron is controlled by three companies only, resulting in high company concentration for traded iron; European Commission 2010a; UNCTAD 2012). In the next section, the methodological framework of the new model introduced in this paper is described.

2.2 Economic impact assessment methodology

For the assessment of economic resource availability, the discussed criteria are transferred into impact categories which are described by characterization models using an analogy to LCA and current life cycle impact assessment (LCIA) methodology. In Table 2, an overview of these impact categories and corresponding category indicators, constituting the core of the characterization model, is presented.

In the context of the assessment of resource availability from a supply risk perspective, a measure to quantify the contribution to the supply risk needs to be included in the characterization model. The category indicator needs to be placed in relation to a target that facilitates an evaluation of risk. Hence, a similar formula as specified in the ecological scarcity method (a "distance-to-target" method) is used by including a threshold or "scale of risk" into the modeling (Frischknecht et al. 2009; Hischier and Weidema 2010; Müller-Wenk 1978). The resulting impact factors (I) are a function of current indicator values and the threshold above which high risk of supply is expected. These factors are calculated for each resource (i) and each impact category (j).

For calculation of the impact factors, the ratio of the current to the critical flow is squared: this means the major exceeding of the target value (implying high risks) is weighted above proportional (see Eq. (1)) (Frischknecht et al. 2009). All indicators are scaled to the range 0 to 1. When needed, order is inverted, such that a higher score corresponds to a high risk (similar to existing methods within LCA). To avoid compensation during further aggregation of impact factors, no values below "1" are permitted in the assessment.

$$I_{i,j} = \mathrm{Max}\left\{\left(\frac{\text{indicator value}_{i,j}}{\text{threshold}_{i,j}}\right)^2; 1\right\} \qquad (1)$$

Resulting supply risk associated with resources is a dimensionless quantity determined exclusively by the ratio of the current indicator value to the determined threshold linked to the life cycle inventory (LCI) (see also Frischknecht et al. 2009). Category indicator results (impact factor × LCI) give an indication about the magnitude of the risk (exceeding of threshold related to the amount of the resources). However, only a comparison of different resources can provide a meaningful estimation of associated supply risks and a basis for decision making. For that purpose and for comparison with conventional resource assessment methods, the different impact categories can be combined to a single "economic resource scarcity potential" (ESP) for each resource, enabling a ranking of overall risk. For calculation of the ESP, impact factors are aggregated using multiplication (see Eq. (2)). A summation of factors would lead to the same ranking, but the relative differences of results would be smaller. As this model will be linked with an LCI that might be dominated by few resources, impact factors need to have a significant margin, so results are not determined only by the specific quantity of resources used.

$$\mathrm{ESP}_i = \prod_j \left(I_{i,j}\right) \qquad (2)$$

Aggregation, as used in this work, implies equal weighting of individual impact factors. This approach can of course be modified as weighting might prove useful with regard to an emphasis of individual aspects or to avoid overvaluation of aspects. While there is controversial discussion about the application of weighting, in the here assessed context regarding the analysis of supply risk of resources independently from LCA, the applied method is meaningful.

2.3 Definition of threshold

The risk threshold provides the advantage of an easy interpretation of results. In Table 3, an overview of thresholds used in

Table 2 Overview of impact categories and indicators

Impact category	Description	Category indicators
Reserve availability	Depletion time (displaying current production technologies)	Reserve-to-annual-production ratio
Recycling	Recycled content of a resource	New material content (%); data as published by UNEP (2011)
Country concentration reserves	Reserve concentration in certain countries	HHI—index is calculated by squaring the market share of each company or country with regard to the production or reserves (USGS 2013) and the summation of the results;
Country concentration mine production	Concentration of mine production in certain countries	
Company concentration mine production	Concentration of mine production in certain companies	
Governance stability	Stability of governance in producing countries (mine production)	WGI—including key dimensions of governance (The World Bank Group 2012) (in this work, an aggregated indicator is used, based on three of the published dimensions that show only very low correlation: voice and accountability, political stability and absence of violence and government effectiveness; aggregation is based on equal weighting)
Socioeconomic stability	Human development in producing countries (mine production)	HDI—combining indicators of life expectancy, educational attainment and income; indicator as published by UNDP (2011)
Demand growth	Increase of demand (past and future)	Percentage annual growth based on past systematics (for basic industrial metals) and future demand scenarios (driven by future technologies) (see Angerer et al. 2009a and Rosenau-Tornow et al. 2009)
Trade barriers mine production	Raw materials underlying trade barriers	Percentage share of mine production under trade barriers; based on data as published by BDI (2010)
Companion metal fraction	Occurrence as companion metal within host metal ore bodies	Percentage of production as companion metal—host metals are copper, aluminum, iron, rare earths, nickel, zinc, lead, magnesium, titanium and tin. Based on data by Hagelüken and Meskers (2010), Reuter et al. (2005), and Erdmann and Behrendt (2010).

this work is given. A threshold above which supply risk is expected is defined for each category indicator. The supply risk for the individual resources is then calculated based on the respective distance to this threshold.

Thresholds are highly system specific: An organization, with a large product portfolio and frequently changing products, would evaluate the risk of supply disruption as less critical than a company with few products and very long development and production life spans (e.g., vehicle production). Furthermore, products with long service lifetimes require stable availability of a required set of resources (Graedel and Erdmann 2012). Thus, even though vulnerability to supply disruptions is not included as a dimension in this work, it is considered implicitly by means of the system-specific determination of thresholds and perception of risk.

Table 3 Determination of thresholds (exemplary, as used in this paper)

Indicator	Threshold and risk
HHI	Low<0.15<high
WGI	Low<0.25<high
HDI	Low<0.12<high
Demand growth (%)	Low<0.01<high
Production under trade barriers (%)	Low<0.25<high
New material content (%)	Low<0.50<high
Companion metal fraction (%)	Low<0.20<high
Depletion time	Low>40>high

Thresholds are based on data by DOJ and FDT (2010), The World Bank Group (2012), UNDP (2011), Rosenau-Tornow et al. (2009), and Daimler AG, 2012, personal communication

The system under study in this paper is the average "global economy." Thus, supply risk is determined as the average global risk. Thresholds are defined based on a general perception of risk in literature and current best practice in industry (Daimler AG, 2012, personal communication; DOJ and FDT 2010; Oryx Stainless 2012; The World Bank Group 2012; UNDP 2011). Setting of thresholds determines the impact factor and thus influences the ESP. To uncover all potential risks, a conservative approach is chosen in this work, and thresholds are selected which are not easy to attain (resulting in a high "distance to the targets").

Results of the aggregated ESP are highly sensitive to the choice of impact categories and indicators as well as to the definition of the risk threshold. Results of the assessment are system specific, and interpretation or comparison of results outside the system has little informative value. The assessment should not be regarded as fixed, situations should be regularly monitored, and indicators have to be updated and thresholds readjusted (see also Rosenau-Tornow et al. 2009).

3 Results

A portfolio of 17 metals is selected based on data availability and also reflecting conducted case studies (Oryx Stainless 2012; Schneider et al. 2011b). In current LCA studies, availability of resources for products or production systems is commonly assessed by means of the abiotic depletion potential (ADP) (CML 2013; Guinée 2002; van Oers et al. 2002). The method is recommended in the Dutch LCA handbook and in the Product Environmental Footprint (PEF) document of the European Commission as current best available practice for assessing resource availability (European Commission 2011, 2013; Guinée 2002). Even though enhancements of this method are published (see Schneider et al. 2011a), use of the conventional ADP is still mainstream practice. Hence, for the comparison of ESP results with commonly applied models, ADP results for the assessed metals are used as reference values. However, results of ADP and ESP are not directly comparable and shall be used complementary as the methods address different dimensions of resource availability.

In Fig. 1, the results of the ESP_{global} are compared to the common $ADP_{ultimate\ reserve}$. The supply risk assessed by means of the ESP_{global} is a dimensionless quantity (see Section 2.2). ADP results are a relative measure with the depletion of the element antimony as a reference (van Oers et al. 2002). The different methods lead to different conclusions. From a geologic perspective, gold is most critical, while rare earths and platinum group metals (PGMs) are associated with the overall highest supply risk.

The magnitude of the ESP_{global} results is high, and any exceeding of the threshold implies a potential risk. Thus, in a second step, results are presented using a logarithmic scale to uncover the risk of all assessed metals (see Fig. 2). ADP results are adapted to fit a logarithmic scale for comparability of results. Based on the aggregated ESP_{global} results presented in Fig. 2, the metals can be ranked according to their risk. For a different resource portfolio, other metals could be identified to bear the highest risk.

Resources delivering the highest ESP_{global} are associated with the highest potential supply risk and thus indicate a need for action. Rare earths for example show a high supply risk in several categories resulting in potential constraints in resource supply. Similar results are found for PGMs. Contrary iron and nickel have low results across most impact categories leading to lower overall supply risk.

To further test and discuss validity of the proposed approach, results are compared qualitatively with supply risks identified in other studies (see Table 4). For this qualitative comparison, the divergence from the threshold in relation to the maximum possible values for individual impact categories is used as a basis. Resources with overall high divergence from these targets are evaluated as risky.

For all approaches, similar results are obtained. Deviations in results can be explained by the system under study, the choice and number of criteria and indicators or the temporal reference. Inclusion of additional indicators can increase or decrease overall supply risk for certain resources in comparison to the assessed resource portfolio. Within the ESP assessment, nickel has a lower relevance than in the study by Erdmann and Behrendt (2010) which could be caused by the consideration of additional categories like trade barriers that lower the relative supply risk of nickel in comparison to other resources in the assessed portfolio (see impact category results displayed in Fig. 3). Likewise, silver for example is evaluated as less risky by the European Commission (2010a) as only four indicators are considered, not including indicators where silver is associated with high supply risk (e.g., companion metal fraction or stability of producing countries). Low- and high-risk areas are only vaguely defined in the studies. A small shift in one of the indicators may result in an increase in overall supply risk and a shift from a low- to a high-risk area (see, e.g., chromium in the study of the European Commission 2010a).

While the ESP has a global focus, other studies assess resource availability for the European Union (European Commission 2010a) or Germany (Erdmann and Behrendt 2010). However, as supply risk is assessed by means of similar criteria within the different studies, the system perspective does not have an important effect on the results.

The comparison verifies that ESP_{global} delivers a valid method and a good basis to comprehensively assess the supply

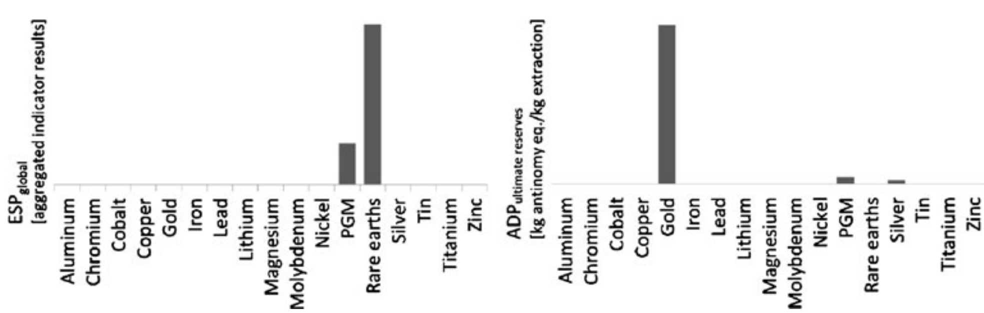

Fig. 1 ESP_{global}* (*left*) vs. $ADP_{ultimate\ reserves}$** (*right*) (data based on CML 2013; Guinée 2002; PE International 2012; van Oers et al. 2002). *Regarding rare earth elements and platinum group metals (PGM), metal groups are assessed instead of individual metals. **For rare earths and PGM, always the raw material of the group with the highest $ADP_{ultimate\ reserves}$ is chosen for comparison

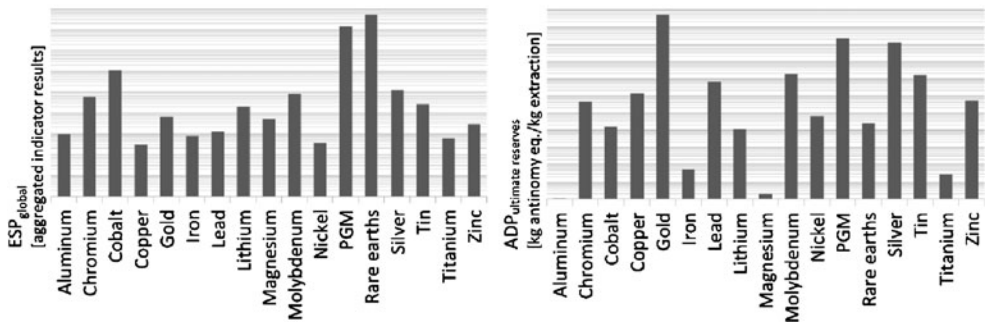

Fig. 2 ESP$_{global}$ (*left*) vs. ADP$_{ultimate\ reserves}$ (*right*) (logarithmic scale)

risk associated with different resources. Results as displayed in Fig. 3 should be regarded as a basis for an analysis of individual impact category results of "risky metals" to identify hotspots and to develop appropriate strategies for risk mitigation (a logarithmic scaling is chosen due to the in parts high range of values of represented data).

4 Conclusions, challenges, and outlook

For sustainable development, an environmental, social, and economic dimension needs to be assessed. Within conventional LCA, resource use is considered from an environmental perspective. The social dimension of resource use is widely discussed, and tools (social LCA) (UNEP 2009b) and several studies exist (GHGm 2008; Kerkow et al. 2012; Tsurukawa et al. 2011) that are linked to the LCA framework. An assessment of economic resource availability considering a life cycle perspective was disregarded so far, and the economic dimension was mainly addressed from a financial perspective (e.g., life cycle costing) or concerning the efficient use of resources. As availability of resources depends on a broad set of economic criteria, this work provided a framework for the assessment of resource beyond existing models. For this purpose, impact categories for modeling the economic dimension of resource provision capability were developed analogously to existing LCA terminology and proceeding. As the new method can be applied in connection with existing life cycle-based approaches, easy implementation is facilitated. By introducing a procedure for the assessment of economic availability of resources, a contribution towards LCSA is made.

Table 4 Qualitative comparison of supply risk as determined in major studies (studies are selected based on transparency of results)

Resource	EU study (4)[a] (European Commission 2010a)	Yale study (6) (Nassar et al. 2012)	IZT study (6) (Erdmann and Behrendt 2010)	ESP$_{global}$[b] (9)
Aluminum	Low		Low	Low
Chromium	Low		High	Medium
Cobalt	High		Medium	High
Copper	Low	Low	Medium	Low
Gold		Low		Low
Iron	Low		Low	Low
Lead			Low	Low
Lithium	Low		Medium	Medium
Magnesium	Low		Low	Low
Molybdenum	Low		Medium	Medium
Nickel	Low		Medium	Low
PGM	High		High	High
Rare earths	High		High	High
Silver	Low	High	High	High
Tin			High	Medium
Titanium	Low		Low	Low
Zinc	Low		Medium	Low

[a] The number in brackets indicates the number of indicators used to determine the supply risk

[b] The basis for this qualitative evaluation is the summarized divergence from the threshold value in relation to the maximum possible value across all impact categories (percent)

Availability of resources differs significantly when economic aspects are taken into account rather than geologic depletion. Detailed assessment of economic criteria influencing resource availability on a product level can be essential to prevent disruptions within the supply chain and help to identify "hotspots" and risks associated with industrial resource use. The ESP approach allows for a more realistic assessment of resource availability, provides a good basis for decision making on a corporate or regional level, and complements current (geologic) resource assessment in LCA.

However, several challenges still occur. The assessment is based on current market analyses for individual resources and is strongly time dependent. Furthermore, a limited set of criteria and indicators is assessed in this work, and focus is on the mine production stage only. For sustainable resource management, all life cycle stages, from resource extraction through production and manufacturing to use and end-of-life treatment (Finkbeiner 2011), need to be analyzed. Each stage of the supply chain has to be assessed. Furthermore, a broader set of criteria and indicators have to be assessed for providing a better picture of supply restrictions.

In this study, the supply risk is captured only at a specific point in time providing short- or medium-term results. As mentioned before, the base period of the study can affect value

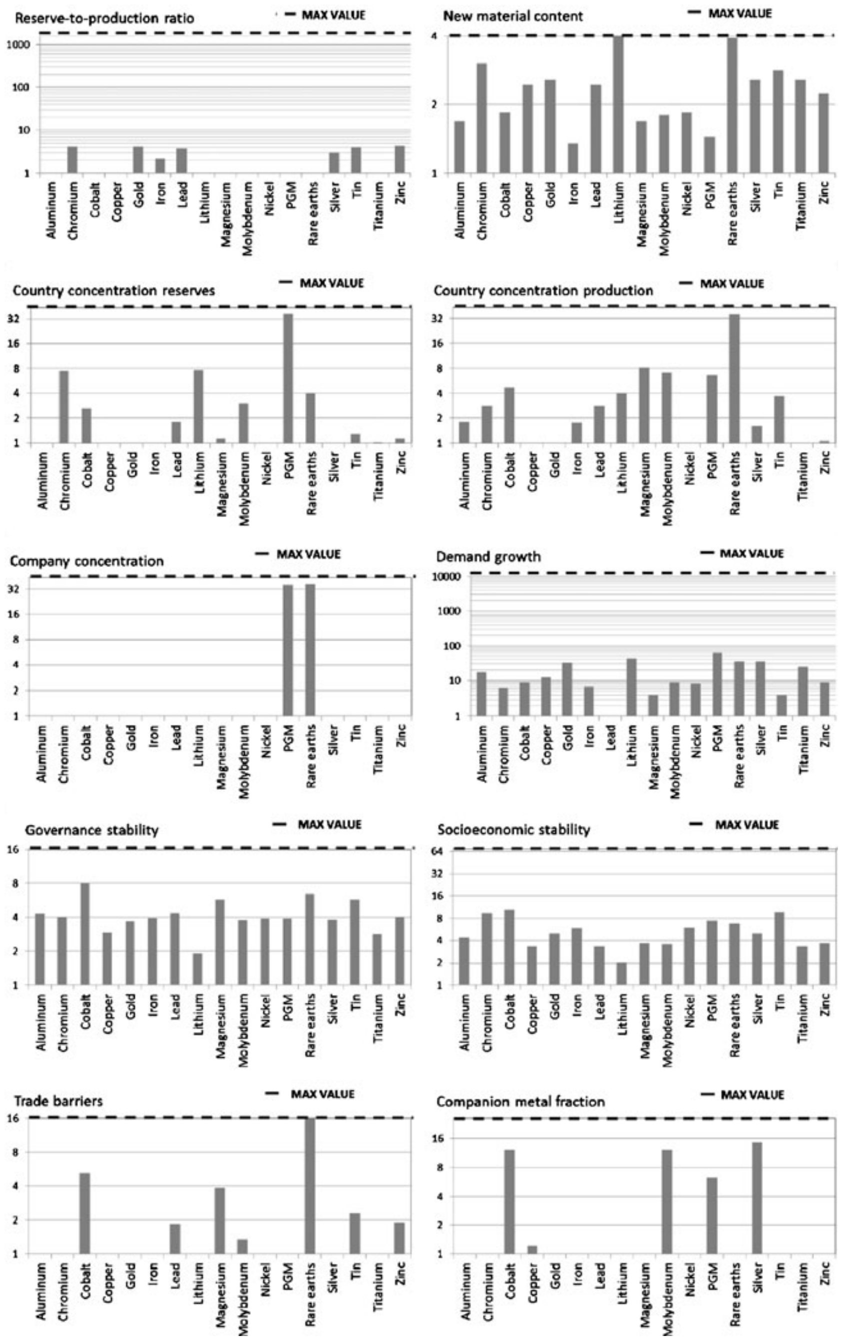

Fig. 3 ESP_{global}: Impact category results in relation to maximum risk value (maximum value is indicated by a black dashed line; values below "1" are associated with no supply risk) (Data based on Angerer et al. 2009a, b; BDI 2010; BGR 2007; CIA 2012; European Commission 2010a; INSG 2012; Nassar et al. 2012; National Research Council 2008; OECD 2009, 2010; POLINARES Consortium 2012; Reuter et al. 2005; The World Bank Group 2012; UNDP 2011; UNEP 2009a, 2011; USGS 2005, 2013)

and relevance of indicators and periodical updates and reconsiderations of data and thresholds are essential.

In addition, future studies need to consider a differentiation of primary and secondary resources. Evaluated criteria mostly refer to primary resource supply only, and some of the developed impact categories are not relevant if only recycled material is used. For the current resource portfolio, the described approach is sufficient, as new material content is high for all resources. However, secondary material, considered as a measure to delay the depletion of primary metal resources, may underlie similar constraints as primary material supply. Thus, a more comprehensive assessment is needed, and primary and secondary materials should be analyzed independently from each other.

Further works will also include the analysis of potential correlations or interrelations of criteria and indicators (to avoid unintended emphasis of certain aspects) and an assessment of temporal sensitivity. Application of this method will be tested further by means of case studies.

References

Angerer G, Erdmann L, Marscheider-Weidemann F, Scharp M, Lüllmann A, Handke V, Marwerde M (2009a) Rohstoffe für Zukunftstechnologien. ISI-Schriftenreihe "Innovationspotenziale". Fraunhofer IRB Verlag, Stuttgart

Angerer G, Marscheider-Weidemann F, Wendl M, Witschel M (2009b) Lithium für Zukunftstechnologien. Fraunhofer ISI, Karlsruhe

BDI (2010) Übersicht über besthende Handels- und Wettbewerbsverzerrungen auf den Rohstoffmärkten. Bundesverband der Deutschen Industrie e.V, Berlin

BGR (2007) Rohstoffwirtschaftliche Steckbriefe für Metall- und Nichtmetallrohstoffe. Bundestanstalt für Geowissenschaften und Rohstoffe, Hannover

BUWAL (1998) Bewertung in Ökobilanzen mit der Methode der ökologischen Knappheit - Ökofaktoren 1997. Schriftenreihe Umwelt, Nr. 297 - Ökobilanzen. Federal Office for Environment Forest and Landscape, Bern

CIA (2012) The world factbook. Central Intelligence Agency

CML (2013) CML - IA 4, 2nd edn. Institut of Environmental Sciences Leiden University, Leiden

Defra (2012) A review of national resource strategies and research. Department for Environment, Food and Rural Affairs, London

DOJ, FDT (2010) Horizontal merger guidelines §5.2. The United States Department of Justice and the Federal Trade Commission, Washington DC

Erdmann L, Behrendt S (2010) Kritische Rohstoffe für Deutschland. Institut für Zukunftsstudien und Technologiebewertung (IZT), Berlin

Erdmann L, Graedel TE (2011) Criticality of non-fuel minerals: a review of major approaches and analyses. Environ Sci Technol 45(18): 7620–7630

European Commission (2010a) Critical raw materials for the EU. Report of the Ad-hoc Working Group on defining critical raw materials

European Commission (2010b) International Reference Life Cycle Data System (ILCD) handbook—framework and requirements for life cycle impact assessment models and indicators. EUR 24709 EN. Luxembourg

European Commission (2011) International Reference Life Cycle Data System (ILCD) handbook—recommendations for life cycle impact assessment in the European context. Publications Office of the European Union, Luxemburg

European Commission (2013) Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations

Finkbeiner M (ed) (2011) Toward life cycle sustainability management. Springer Science+Business Media, Berlin

Finnveden G (2005) The resource debate needs to continue. Int J Life Cycle Assess 10(5):372

Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in life cycle assessment. J Env Mgmt 91:1–21

Frischknecht R, Steiner R, Jungbluth N (2009) The ecological scarcity method: Eco-Factors 2006—a method for impact assessment in LCA. Environmental studies no. 0906. Federal Office for the Environment (FOEN), Bern

GHGm (2008) Social and environmental responsibility in metals supply to the electronic industry. GreenhouseGasMeasurement.com (GHGm), Guelph, Canada

Goedkoop M, Spriensma R (2001) The eco-indicator 99—a damage oriented method for life cycle impact assessment, vol 3. PRé Consultants B.V, Amersfoort

Graedel TE, Barr R, Chandler C, Chase T, Choi J, Christofferson L, Friedlander E, Henly C, Jun C, Nassar NT, Schechner D, Warrne S, Yang M-y, Zhu C (2012a) Methodology of metal criticality determination. Environ Sci Technol 46:1063–1070

Graedel TE, Barr R, Chandler C, Chase T, Choi J, Christofferson L, Friedlander E, Henly C, Jun C, Nassar NT, Schechner D, Warrne S, Yang M-y, Zhu C (2012b) Methodology of metal criticality determination—supporting information

Graedel TE, Erdmann L (2012) Will material scarcity impede routine industrial use? MRS Bull 37:325–331

Guinée JB (ed) (2002) Handbook on life cycle assessment—operational guide to the ISO standards. Kluwer Academic Publishers, Dordrecht

Hagelüken C, Meskers CEM (2010) Complex life cycles of precious and special metals. In: Graedel TE, Voet E (eds) Linkages of sustainability. MIT Press, Cambridge, pp 163–197

Hauschild M, Wenzel H (1998) Environmental assessment of products. Chapman & Hall, New York

Hischier R, Weidema B (2010) Implementation of life cycle impact assessment methods. ecoinvent report no. 3. ecoinvent centre, St. Gallen

INSG (2012) International Nickel Study Group. www.insg.org

ISO (2006a) Environmental management—life cycle assessment—principles and framework. ISO 14040:2006. European Committee for Standardisation, Brussels

ISO (2006b) Environmental management—life cycle assessment—requirements and guidelines. ISO 14044:2006. European Committee for Standardisation, Brussels

Kerkow U, Martens J, Müller A (2012) Vom Erz zum Auto - Abbaubedingungen und Lieferketten im Rohstoffsektor und die Verantwortung der deutschen Automobilindustrie. MISEREOR e.V., "Brot für die Welt". Global Policy Forum, Aachen

Klinglmair M, Sala S, Brandao M (2013) Assessing resource depletion in LCA: a review of methods and methodological issues. Int J Life Cycle Assess, published online

Müller-Wenk R (1978) Die ökologische Buchhaltung: Ein Informations- und Steuerungsinstrument für umweltkonforme Unternehmenspolitik. Campus Verlag, Frankfurt

Nassar NT, Barr R, Browning M, Diao Z, Fiedlander E, Harper EB, Henly C, Kavlak G, Kwatra S, Jun C, Warren S, Yang M-Y, Graedel TE (2012) Criticality of the geological copper family. Environ Sci Technol 46(2):1071–1078

National Research Council (2008) Minerals, critical minerals, and the U.S. economy. National Academies Press, Washington, DC

OECD (2009) Workshop on raw materials. Paris

OECD (2010) The economic impact of export restrictions on raw materials. OECD Trade Policy Studies. OECD Publishing, Paris

Oryx Stainless (2012) Key raw materials nickel, chrome and iron: Limited availability despite sufficient geological reserves. Oryx Stainless Group, Mühlheim an der Ruhr/Dordrecht

PE International (2012) GaBi 5 software-system and database for life cycle engineering. Stuttgart, Echterdingen

POLINARES Consortium (2012) Fact sheet: copper. POLINARES working paper n. 40

Reuter MA, Heiskanen K, Boin U, Schaik A, Verhoef E, Yang Y, Georgalli G (2005) The metrics of material and metal ecology. Developments in mineral processing 16. Elsevier, Amsterdam

Rosenau-Tornow D, Buchholz P, Riemann A, Wagner M (2009) Assessing the long-term supply risks for mineral raw materials—a combined evaluation of past and future trends. Resour Policy 34: 161–175

Sala S (2012) Assessing resource depletion in LCA: a review of methods and methodological issues. In: Mancini L, De Camillis C, Pennington D (eds) Security of supply and scarcity or raw materials.

Towards a methodological framework for sustainability assessment. European Commission, Joint Research Center, Institute for Environment and Sustainability. Publication Office of the European Union, Luxemburg, pp 24–27

Schneider L, Berger M, Finkbeiner M (2011a) The anthropogenic stock extended abiotic depletion potential (AADP) as a new parameterisation to model the depletion of abiotic resources. Int J Life Cycle Assess 16(9):929–936

Schneider L, Berger M, Finkbeiner M (2011b) Economic material availability as a new area of protection for life cycle sustainability assessment. Paper presented at the SETAC Europe 21st Annual Meeting, Milano, 15–19 May

Schneider L, Berger M, Finkbeiner M (2013) Measuring resources scarcity—limited availability despite sufficient reserves. In: Mancini L, DeCamillis C, Pennington D (eds) Security of supply and scarcity or raw materials. Towards a methodological framework for sustainability assessment. European Commission, Joint Research Center, Institute for Environment and Sustainability. Publications Office of the European Union, Luxemburg, pp 32–34

Steen BA (2006) Abiotic resource depletion—different perceptions of the problem with mineral deposits. Int J Life Cycle Assess 11(1):49–54

Stewart M, Weidema B (2005) A consistent framework for assessing the impacts from resource use, a focus on resource functionality. Int J Life Cycle Assess 10(4):240–247

The World Bank Group (2012) Worldwide governance indicators

Tsurukawa N, Prakash S, Manhart A (2011) Social impact of artisanal cobalt mining in Katanga, Democratic Republic of Congo. Öko-Institut e.V, Freiburg

Udo de Haes HA, Jolliet O, Finnveden G, Goedkoop M, Hauschild M, Hertwich EG, Hofstetter P, Klöpffer W, Krewitt W, Lindeijer EW, Mueller-Wenk R, Olson SI, Pennington DW, Potting J, Steen B (2002) Life cycle impact assessment: striving towards best practice. Society of Environmental Toxicology and Chemistry, Pensacola

UNCTAD (2012) Iron ore production and trade set new records in 2011. United Nations Conference on Trade and Development, Geneva

UNDP (2011) Human development report 2011—sustainability and equity: a better future for all. New York

UNEP (2009a) Critical metals for future sustainable technologies and their recycling potential. Sustainable innovation and technology transfer industrial sector studies. United Nations Environment Programme and Öko-Institut e.V., Paris, Darmstadt

UNEP (2009b) Guidelines of social life cycle assessment. UNEP/SETAC Life Cycle Initiative at UNEP, CIRAIG, FAQDD and the Belgium Federal Public Planning Service Sustainable Development, Paris

UNEP (2010) Assessing the environmental impacts of consumption and production; priority products and materials. A Report of the Working Group on the Environmental Impacts of Products and Materials to the International Panel for Sustainable Resource Management. Hertwich E, van der Voet E, Suh S, Tukker A, Huijbregts M, Kazmierczyk P, Lenzen M, McNeely J, Moriguchi Y, Paris

UNEP (2011) Recycling rates of metals—a status report. United Nations Environmental Programme, International Resources Panel, Paris

USGS (2005) Minerals yearbook. Volume I, metals and minerals. United States Geological Survey, Reston

USGS (2013) Mineral commodity summaries 2013. U.S. Geological Survey, Department of the Interior, Reston

van Oers L, deKoning A, Guinée J, Huppes G (2002) Abiotic resource depletion in LCA. Road and Hydraulic Engineering Institute, Leiden

VDI (2013) http://www.vdi.de/technik/fachthemen/energie-und-umwelt/fachbereiche/ressourcenmanagement/themen/richtlinienwerk-zur-ressourceneffizienz-zre/. Accessed 22 Apr 2013

von der Lippe P (1993) Deskriptive Statistik. Gustav Fischer Verlag, Stuttgart

Weidema B, Finnveden G, Stewart M (2005) Impacts from resource use—a common position paper. Int J Life Cycle Assess 10(6):382

Yellishetty M, Mudd GM, Ranjith PG (2011) The steel industry, abiotic resource depletion and life cycle assessment: a real or perceived issue? J Clean Prod 19:78–90